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DEVELOPMENT OF EMISSION FACTORS FOR ESTIMATING ATMOSPHERIC EMISSIONS FROM FOREST FIRES

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This report contains emission factors (weight of pollutant per acre burned) for estimating atmospheric emissions from forest fires (especially wildfires) for each of the ten U. S. Forest Service regions in the U. S. The pollutants considered are: total particulates, hydrocarbons, carbon monoxide, nitrogen oxides, and sulfur oxides. Data on acreage consumed by wildfires are used with the factors to estimate mass emissions for each region. The effects of such variables as terrain, density of vegetation coverage, type of vegetation, wind speed, and humidity are also discussed. Finally, proposed approaches to mathematically correlate these variables (via empirical and theoretical models) with both emission factors and mass emissions are presented.

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Prepared for

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Office of Air and Water Programs
Office of Air Quality Planning and Standards
Research Triangle Park, N. C. 27711

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FOREWORD

This report has been prepared for the Environmental Protection Agency, under Contract No. 68-02-0641, to describe work performed on IITRI Project No. C6265, "Development of Emission Factors for Estimating Atmospheric Emissions from Forest Fires", during the period 29 June 1972 to 27 July 1973.

Significant amounts of pollutants, both natural and man-made, are released into the atmosphere. In order to obtain a detailed knowledge of all known sources, the Office of Air Quality Planning and Standards, Monitoring and Data Analysis Division, is responsible for developing and reporting emission factors that are used with production or consumption data or other "activity level" indicators to make estimates of the amounts of pollutants which are released to the atmosphere. The specific objective of this study is to develop emission factors for estimating emissions from various types of forest fires.

At the present time, much of the available information concerns industrial (man-made) pollutants. However, in certain urban areas in near proximity to forest areas, an additive effect of increased concentration of pollutants or a reactive effect due to the mixture of urban pollution with combustion products of a forest fire may result. Examples of this were seen in the Florida Everglades fires and the tourist cities of the East Coast of Florida, or the brush fires of southern California on the periphery of the Los Angeles basin. Other less newsworthy occurrences are frequent in residential towns located downwind of forest fires.

Many of the references on the total mass of emissions from wildfires differ by several orders of magnitude, and deficiencies can be found in their values. To correct these deficiencies and to increase the overall air pollution knowledge regarding the forest fire emissions, a compilation and documentation of the emission factors of various pollutants as it relates to various types of forests undergoing combustion is necessary.

No intentional attempt is made to justify, qualify, or negate the use of "prescribed" forest fires by emphasis of the emissions produced by forest fires. The attempt is made, however, to develop the most realistic emission values based on the present state-of-the-art. No bias "for-or-against" prescribed burning is stated or implied.

The cooperation and help received from personnel in the U.S. Forest Service, universities, research stations, and other friends are gratefully acknowledged. A special thanks goes to Dr. Robert W. Cooper and the staff of the Southern Forest Fire Laboratory in Macon, Georgia; to Dr. Ellis F. Darley and the staff of the Statewide Air Pollution Research Center in Riverside, California; and to Dr. Edwin V. Komarek, Sr., and the staff of Tall Timbers Research Station in Tallahassee, Florida, for conducting demonstration burns, emission testing of burning forest fuels, and informative discussions on emissions from forest fires.

We gratefully acknowledge the guidance and many helpful suggestions offered by William Vatavuk, Project Officer, and James Southerland, Chief, Emissions Section, National Air Data Branch, of the EPA.

Personnel working on this program were: Dave Becker and Patricia Llewellen, Information Sciences; Arthur Takata and Thomas Waterman, Fire Research; and John Stockham and George Yamate, Fine Particles Research. Conceptual mathematical models were initiated by D. Becker and A. Takata as a first step in predicting output of emissions from fuel and fire behavior models.

Respectfully submitted,
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DEVELOPMENT OF EMISSION FACTORS FOR ESTIMATING ATMOSPHERIC EMISSIONS FROM FOREST FIRES

ABSTRACT

The objective of this project was to develop emission factors (weight of pollutant per acre burned) for estimating emissions from forest fires, especially wildfires. The pollutants of interest were particulates (filterable and total), hydrocarbons (reactive or unreactive), carbon monoxide, nitrogen oxides, and sulfur oxides. The effects of terrain, density of vegetation coverage, type of vegetation, wind speed, and humidity were to be expressed as adjustment factors to the average emission factors. Also, emission factors were to be developed for the five geographical forest areas of the country. Information from the literature and unpublished test work were to be used to develop the emission factors.

The information sought for each forest area were:

1. The number of acres burned by wildfires.
2. The quantity of fuel available, or preferably, the fuel consumed by the average wildfire.
3. Measurements of emissions from burning forest fuels.
4. The effect of fire behavior variables on emissions

Acres consumed by wildfires for each geographical forest area were obtained from a compilation of wildfire statistics prepared by the Division of Cooperative Forest Fire Control of the USDA Forest Service. No comparable set of statistics was available for acreage burned by "managed" fires.

Fuel data were also obtained from Forest Service reports and contacts with regional Forest Service laboratories and personnel. The Forest Service periodically undertakes a forest survey of commercial timber and studies forest fuels

for fire prediction, prevention, and control. They now consider fuel assessment to be of major importance. Past and present fire reports describe fuels by forest tree type. However, the National Fire Danger Rating System (NFDR) is now operational and each region measures standing timber and fuels for use in fire models. These models recognize the importance of the size of forest fuels rather than type. They emphasize the fine forest fuels with a tendency to burn, rather than the amount potentially able to burn.

The emissions produced by the burning of forest fuels were obtained through an intensive information search and site visits to several fire laboratories. No emission data were available from wildfires. Experimental measurements of the emissions were tabulated for comparison and found to be consistent, with the exception of the values for carbon monoxide. Carbon monoxide is an anomaly, since burning behavior (temperature, duration, and oxygen supply) and the point of sampling radically alter the results. During informal discussions at the 13th Tall Timbers Fire Ecology Conference, references were made to the close agreement among emission measurements made at the Southern Forest Fire Laboratory, the bushfire smoke studies by an Australian study team, and the results reported by Dr. E. F. Darley at the University of California, Riverside. Emissions per ton of forest fuel appear to be independent of tree type and other variables, from a practical viewpoint. Using our best engineering judgement, the following emission values or pollutant yields were selected as representative of average forest fuels:

Pollutant	Pollutant Yield, lbs/ton of fuel
Total Particulate	17
Carbon Monoxide	140
Total Hydrocarbon (as CH_4)	24
Nitrogen Oxides (as NO_x)	4
Sulfur Oxides (as SO_2)	Neg.

The emission factors and the total emissions produced from a forest fire for each geographic region in the United States were calculated from the formulas:

1. Emission Factor (lb/acre) = Pollutant Yield (lbs/ton) x Fuel Consumed (tons/acre)
2. Total Emissions (tons) = Emission Factor (lbs/acre) x Number of Acres Burned (Acres) x Constant (1 ton/2000 lbs)

No data were available that distinguished between filterable and total particulates. Evidence, based on one sample collected from burning wood chips and shavings, is that the geometric mass mean radius of the particulates is about 0.035 μm. Because of difficulties in interpreting analytical and reporting procedures, an estimate of reactive and nonreactive hydrocarbons was impossible.

Fire behavior variables have not been correlated with emissions. The consumable fuel and moisture content appear to have significant effects, while terrain and wind speed have minimal effects. "Green" vegetation produces about three times the quantities of particulates as "dead", dry materials. However, the emission factors tabulated represent moisture levels common to fuels consumed by wildfires. Our understanding of how fire behavior variables affect emissions is insufficient to develop correction factors at this time. Their use would only serve to complicate the emission estimates without improving the reliability of the data.

The following table is a complete summary of the wild fire emission data by geographical subdivision. The table shows acres consumed by wildfires in 1971; wildfire fuel consumption; emission factors for particulates, carbon monoxide, hydrocarbons, and nitrogen oxides; and emissions for 1971.

COMPLETE SUMMARY OF EMISSIONS AND EMISSION FACTORS

Geographic Area	Forest Vegetation of the U.S. (Appendix B)	** Acreage Consumed by Wildfire (acres)	Wildfire Fuel Consumption (tons/acre)	Pollutants							
				Emission Factors				** Emissions			
				Particulate 17 #/Ton* (#/acre)	CO 140 #/Ton* (#/acre)	H-C *** 24 #/Ton* (#/acre)	NO_x 4 #/Ton* (#/acre)	Particulate (tons)	CO (tons)	H-C *** (tons)	NO_x (tons)
1) Rocky Mountain Group	Western Larch-Western White Pine; Ponderosa Pine-Douglas Fir; Lodgepole Pine; Pinyon-Juniper	774,405	37	629	5,180	888	148	243,550	2,005,709	343,836	57,306
Northern, Region 1		351,563	60	1,020	8,400	1,440	240	179,297	1,476,560	253,125	42,187
Rocky Mountain, Region 2		162,795	30	510	4,200	720	120	41,513	341,870	58,606	9,768
Southwestern, Region 3		206,983	10	170	1,400	240	40	17,593	144,887	24,843	4,140
Intermountain, Region 4		53,064	8	136	1,120	192	32	3,608	29,716	5,094	849
2) Pacific Group	Ponderosa Pine-Douglas Fir; Pacific Douglas Fire; Redwood; Ponderosa Pine-Sugar Pine; Pinyon-Juniper-Chaparral	1,161,138	19	323	2,660	456	76	187,524	1,544,314	264,739	44,123
California, Region 5		46,941	18	306	2,520	432	72	7,182	59,144	10,139	1,690
Alaska, Region 10		1,046,542	16	272	2,240	384	64	142,330	1,172,127	200,936	33,489
Pacific N.W., Region 6		67,655	60	1,020	8,400	1,440	240	34,504	284,147	48,712	8,118
3) Southern Group	Oak-Hickory; Oak-Pine; Longleaf-Loblolly-Slash Pine; Cypress-Tupelo-Sweetgum; Chestnut-Chestnut Oak-Yellow Poplar; Mangrove	1,992,339	9	153	1,260	216	36	152,414	1,255,179	215,173	35,862
Southern, Region 8 (Group and Region are the same)		1,992,339	9	153	1,260	216	36	152,414	1,255,179	215,173	35,862
4) North Central Group	Spruce-Fir; Jack, Red, and White Pine; Birch-Beech-Maple-Hemlock; Oak-Hickory; Chestnut-Chestnut Oak-Yellow Poplar	232,749	11	187	1,540	264	44	21,762	179,217	30,723	5,120
Eastern, Region 9 (Both Groups are in Region 9)		349,000	11	187	1,540	264	44	32,632	268,730	46,068	7,678
5) Eastern Group (with Region 9)	Chestnut-Chestnut Oak-Yellow Poplar; Birch-Beech-Maple-Hemlock; Spruce-Fir	116,251	11	187	1,540	264	44	10,870	89,513	15,345	2,558
6) Total United States		4,276,882	17	289	2,380	408	68	618,009	5,089,490	872,484	145,414

* Pollutant Yield, lb pollutant/ton fuel consumed

** Acreage Consumed by Wildfire and Emissions are for 1971.

*** Hydrocarbon as methane

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GLOSSARY

For a more extensive and complete terminology, the Society of American Foresters, 1010 Sixteenth Street, N.W., Washington, D.C. 20036, has a publication, "Terminology of Forest Science, Technology, Practice and Products", that is used as a standard for forestry concepts.

ambient	the surrounding, enveloping conditions. As they pertain to weather at the earth's surface, the conditions measured in the instrument shelter are considered to be ambient.
blow-up	the very rapid escalation of a surface fire (ground fire) into a crown fire.
branches	1" to 3" diameter material.
brush	scrub vegetation and stands of tree species that do not produce merchantable timber. (Not a synonym for slash.)
burn	the application of fire to fuel.
agricultural burn	a managed burn of residues derived from an agricultural operation.
controlled burn	a directed and restrained application of fire to fuel.
hazard reduction burn	a managed burn of litter and underbrush in order to prevent fuel buildup in the forest and reduce the hazards of a wildfire.
managed burn	an overall designation for a man-administered combustion (burning) operation for some utilitarian purpose. Many times the term is used synonymously with controlled burning or regulated burning.
orchard pruning burn	a specific type of agricultural burn as applied to the burning of prunings and other wastes derived from good orchard practices.

prescribed burn	the generally recognized managed burn that is often called "prescription burning". This is a low to medium intensity surface fire initiated to carry out a variety of sound forestry concepts and to simulate a natural fire control method.
range rehabilitation burn	the managed burning of undesirable non-timber trees and shrubs that reduce the value of a range.
slash burn	a managed burn of residue remaining after a logging or thinning operation.
burning index (BI)	a number related to the amount of effort needed to contain a fire of a particular fuel type within a rating area. A doubling of the BI indicates that twice the effort will be needed to contain a fire of that fuel type as was previously required.
chaparral	a loose term denoting a variety of brush and shrub species; principally scrub oak, manzanita, sumac, cliffrose, ceanothus, and chamise.
clearcutting	a controversial type of forest management practice in timber harvesting whereby an entire area is cut completely.
duff	the partially decomposed organic material of the forest floor beneath the litter of freshly fallen twigs, needles, and leaves. (The F and H layers of the forest floor.)
emission factor	the pounds of a pollutant emitted to the atmosphere from burning an acre of forest land.
energy release component (ERC)	a number related to the rate of heat release (BTU per second) per unit area (square foot) within the flaming front at the head of a moving fire. The expression differs from that of intensity (see intensity) but is indicative of how "hot" a fire is burning.

equilibrium moisture content (EMC)	the moisture content that a fuel particle would attain if exposed for an infinite period in an environment of specified constant temperature and humidity. When a fuel particle has reached its EMC, there is no net exchange of moisture between it and its environment.
fire	the burning of a combustible body.
backfire	a managed burn utilized in the removal of fuel concentrations, usually in forest fire fighting in which the fire is set to travel on the ground and against the wind.
firebrand	any source of heat, natural or man-made, which is capable of igniting wildland fuels.
crown fire	fire starting on the surface and burning vertically into the crown layer (tree tops) of the forest. A crown fire requires the support of surface fires.
head fire	a managed burn set to travel on the ground and with the wind.
mass fire	large area actively burning at the same time.
surface fire	fire burning mostly in the duff or litter of fallen leaves, needles, and twigs and the undergrowth of the forest floor -- a ground fire.
fire intensity	energy release per unit time per unit length of fire front. (Includes the depth of flame behind the fire front.)
flaming front	that zone of a moving fire within which the combustion is primarily flaming. Behind the flaming front combustion is primarily glowing.
forb	a nongrasslike herbaceous plant.
forest floor layer	accumulation of dead organic plant matter above the mineral soil. The layer is composed of parts called the L, F, and H layers.

L layer	this is the litter layer and is composed of unaltered organic plant matter -- top layer.
F layer	this is the fermentation layer and is composed of partly decomposed plant matter -- middle layer.
H layer	this is the humus layer and is composed of well decomposed plant matter -- above the mineral soil.
fuel	a body of combustible material.
fuel assessment	an experienced evaluation (inventory) of the type and quantity of combustible material (fuel loading) present in a forest area for a "possible" fire situation.
available fuel	the portion of the total fuel that actually burns; fuel which will be consumed under a given set of or prevailing weather conditions.
fuel class	a group of fuels possessing common characteristics. In the NFDR System, dead fuels are grouped according to their timelag (1-, 10-, and 100-Hr.) and living fuels by whether they are herbaceous or woody.
dead fuel	naturally occurring fuel in which the moisture content is governed almost entirely by atmospheric moisture (relative humidity and precipitation).
fine fuel	the complex of living and dead herbaceous plants and dead woody plant materials less than one-fourth inch in diameter.
fine fuel moisture	the probably moisture content of fast-drying fuels which have a timelag constant of 1 hour or less; such as grass, leaves, ferns, tree moss, draped pine needles, and small twigs
herbaceous fuels	undecomposed material, living or dead, derived from herbaceous plants.

living fuel	naturally occurring fuel in which the moisture content is physiologically controlled within the living plant. The NFDR System considers only herbaceous plants and woody plant material which is small enough (leaves and needles, and twigs less than one-fourth inch in diameter) to be consumed in the flaming front of an initiating fire.
fuel loading	amount of fuel (combustible matter) present in a defined area -- in the context of this report, it is synonymous with "available fuel" per acre in that it is the specified estimated fuel tonnage which will be consumed in a wildfire.
fuel model	a simulated fuel complex for which all the fuel descriptors required for the solution of the mathematical fire spread model have been specified.
fuel moisture content (also fuel moisture)	the quantity of water in a fuel particle expressed as a percent of the ovendry weight of the fuel particle.
one-hour timelag fuel moisture (1-hr. TL FM)	the moisture content of the 1-hour timelag fuels.
one-hour timelag fuels	fuels consisting of dead herbaceous plants and roundwood less than about one-fourth inch in diameter. Also included is the uppermost layer of needles or leaves on the forest floor.
one-hundred hour timelag fuel moisture (100-hr. TL FM)	the moisture content of the 100-hour timelag fuels.
one-hundred hour timelag fuels	dead fuels consisting of roundwood in the size range of 1 to 3 inches in diameter and very roughly the layer of litter extending from approximately three-fourths inch to 4 inches below the surface.
fuel particles	the wide variety of living and dead plant parts that exist in the forest.

potential fuel	combustible material of large dimension that is considered fuel but would not burn completely even in an intense wildfire.
ten-hour timelag fuel moisture (10-hr. TL FM)	the moisture content of the 10-hour timelag roundwood fuels.
ten-hour timelag fuels	dead fuels consisting of roundwood in the size range of one-fourth to 1 inch and very roughly the layer of litter extending from just below the surface to approximately three-fourths inch below the surface.
total fuel	combustible material that would burn under the most severe weather and burning conditions.
herb	a plant which does not develop woody, persistent tissue but is relatively soft or succulent and sprouts from the base or develops from seed (annuals) each year. Included are grasses, forbs, and ferns.
humidity	a measure of water-vapor content of the air.
hydrocarbon, reactive	gas phase hydrocarbon (organic compound) reactive in the photochemical reaction system, for example, olefins.
hydrocarbon, non-reactive	gas phase hydrocarbon (organic compound) inert in the photochemical reaction system, for example, methane.
ignition component (IC)	a number related to the probability that a spreading fire will result if a firebrand encounters fine fuel.
initiating fire	a wildfire which exhibits reasonably predictable behavior (no crowning or spotting).
insolation	solar radiation received at the earth's surface.

land classifications

commercial forest land	forest land that is producing, or is capable of producing, crops of industrial wood and is not withdrawn from timber use by statute or administrative regulation. Includes areas suitable for management to grow crops of industrial wood and generally capable of producing in excess of 20 cubic feet per acre of annual growth. Includes both accessible and prospectively accessible areas and both operable and prospectively operable areas. (USFS Forest Survey.)
noncommercial forest land	unproductive forest land incapable of yielding crops of industrial wood because of adverse site conditions, and productive forest land withdrawn from commercial timber use through statute or administrative regulation. (USFS Forest Survey.)
litter	the top layer of the forest floor, composed of loose debris including dead sticks, branches, twigs and recently fallen leaves or needles; little altered in structure by decomposition. (The L layer of the forest floor.)
National Fire Danger Rating System (NFDR System)	the U.S Forest Service system using fuel models to standardize fuel descriptions from which to develop fire behavior components and indices to aid in planning supervisory fire control activities on a fire protection unit.
natural abatement	treatment of residue by natural decay and deterioration -- will require a long period of fire protection so that it will not be a large fuel source.
oven dry fuel weight	weight of fuel sample obtained by the oven drying technique.
oven drying technique	method to determine the moisture content of fuel by oven-drying at 100-105°C until constant weight is obtained.

pollutant yield	the emissions associated with the burning of the available forest fuel. The yield, reported in lbs/ton, appears to be independent of tree type and other variables associated with forest fires. Often this relationship is termed the emission factor. However, for this study, the emission factors relate the pollutants emitted per acre burned.
protection unit	a geographical area which is administratively defined and which is the smallest area for which organized fire suppression activities are formally planned.
relative humidity (RH)	the ratio of the actual amount of water vapor in the air to the amount necessary to saturate the air at that temperature expressed as a percentage.
residence time	(1) the time required for the flaming zone of a fire to pass a stationary point, (2) the width of the flaming zone divided by the rate of spread of the fire.
shrub	a woody perennial plant differing from a perennial herb by its persistent and woody stem, and from a tree by its low stature and habit of branching from the base.
silviculture	the cultivation of forest trees; forestry; arboriculture.
slash	branches, bark, tops, chunks, cull logs, uprooted stumps, and broken or uprooted trees left on the ground after logging; also debris resulting from thinnings, wind, or fire.
slope	the variation of terrain from the horizontal; the number of feet rise or fall per 100 feet measured horizontally, expressed as a percentage.
spread component (SC)	a number related to the forward rate of spread of the head of a fire.
sticks	a piece of wood generally long and slender.

timelag (TL)	the time necessary for a fuel particle to lose approximately 63 percent of the difference between its initial moisture content and its equilibrium moisture content.
volatiles	readily vaporized organic materials which, when mixed with oxygen, are easily ignited.
wildfire	any fire that burns uncontrolled in vegetative or associated flammable material.
average wildfire	wildfire that does not generate special emergency measures by the fire control officer.

DEVELOPMENT OF EMISSION FACTORS FOR ESTIMATING ATMOSPHERIC EMISSIONS FROM FOREST FIRES

1. INTRODUCTION

The object of this project is to develop emission factors for use in estimating atmospheric emissions from forest fires, especially "wild fires". To develop reliable emission factors, it is necessary to measure the emissions and to determine the variables associated with "wild fires" and how they affect the quantities of emissions released to the atmosphere. Some of these variables are: fuel concentration, arrangement, and type; moisture content of the fuel and environment; wind speed; and terrain.

1.1 Background

The Office of Air Quality Planning and Standards, Monitoring and Data Analysis Division of the Enviromental Protection Agency is responsible for developing and reporting emission factors. The Environmental Protection Agency (EPA) defines the emission factor as, "a statistical average of a quantitative estimate of the rate at which a pollutant is released to the atmosphere as a result of an activity such as combustion or industrial production, divided by the level of that activity". The emission factor thus relates the quantity of pollutants emitted to some indicator such as production capacity, quantity of fuel burned, or, in the case of forest fires, to the number of acres burned. In general, emission factors are not precise indicators of emissions from a single source, but are more valid when applied to a large number of sources and processes and can be useful in conducting source inventories in pollution studies. A collection of emission factors has been published by the EPA (1).

In order to define problem areas in air pollution, an emission inventory is maintained to determine sources and components of air pollution. The emission inventory is a detailed and descriptive information catalog regarding emission sources, pollutant types, location, quantities, frequency, duration, and relative impact of these emissions to air quality.

The emission inventory is an important planning tool available to an air pollution control agency. It can be used to design an air sampling network; to predict ambient air quality; to design, evaluate, or modify a control program; and provide information on major sources of pollution.

Forest fires are a major natural source of air pollutants. A "wild fire", or uncontrolled fire, is a large scale natural combustion process of various ages, sizes, and types of botanical specimens growing outdoors in a defined geographical area. Thus, the burning characteristics (intensity, spread, etc.) are closely interrelated to the fuel quality and history, meteorological conditions and history, and the physical locality in terms of climatology and physical topography. Each factor is dependent on the others; a change in one results in a change in others, with subsequent reaction.

The fire behavior thus will be the sum total of the various factors and will be regulated to the extent determined by the influence of the dominant factor. For example, a high moisture level, or the lack of fuel, or a physical obstacle may dominate and result in a fire being stopped. In an extremely intense fire such as a "blow-up" fire, all factors may be conducive to combustion and thus result in extreme fire intensity and the consumption of numerous acres of forest.

The atmospheric emissions from this complex combustion process are thus difficult to measure and "control" as compared to man-made mobile and stationary sources of combustion (2,3,4,5,6,7,8).

From a naturalist's perspective, forest fires can be considered natural phenomena. Dynamic and living, they require space, time, fuel (food), and the proper environment to grow, sustain themselves, and finally die. The fuel character (plant community) appears to be the least difficult parameter for people to manipulate as an essential component in the natural sequence of fire ignition, spread, and extinguishment. Nature itself spawns a forest fire, nurses it, propagates it, and finally kills it.

Fuel, weather, and topographic factors are discussed from a naturalistic viewpoint in several papers that treat fire as a natural phenomenon (9,10,11,12).

1.2 Overview Information

There was a lack of published information on the quantities and types of pollutants generated from forest fires. The information search revealed a lack of pertinent experimental data on the emissions from wild fires. Data and measurements reported in the literature have been obtained on laboratory fires, burning towers, slash fires, and prescribed burns. Other reported emission data have been estimates derived from experience and knowledge of the combustion of woody fuels and the estimated fuel tonnages in the forest areas of the country.

The fundamental information needed for this project were:

a) acreage burned;

b) quantity of fuel (% consumed -- burned);

c) measured emissions per quantity of fuel; and

d) fire behavior factors affecting emissions.

2. INFORMATION SEARCH

Prior to the initiation of the project, communication links were established with sources that could provide information pertinent to the program scope. A rapid literature survey was made at the John Crerar Library, located on the IIT Campus. Telephone calls were also made to colleagues knowledgeable in the areas of forest fires, mass fires, and atmospheric research to determine the sources and availability of relevant information.

Upon project initiation, an information retrieval strategy was undertaken. Under an overall plan, the search was divided into four interrelated categories to systematize the intensive retrieval of related, useful information. These categories were: literature surveys, site visits, letters and telephone calls of inquiry, and personal contacts.

2.1 Literature Survey

Although the program was to focus on "wild fires", data on "prescribed burning", controlled outdoor fires, industrial processing, and wood chemistry were also retrieved to broaden the range of physical conditions represented and to describe the processes at work. In addition, information relative to forest fire behavior, forest fire meteorology, and forest type vegetation in various geographic areas were sought.

The entire set of the Air Pollution Abstracts (and the NAPCA Abstracts) were searched comprehensively. This search yielded more than 100 relevant citations. Next, the Fire Research Abstracts were searched, beginning with the 1961 issues and continuing through the present. This search yielded about 70 additional citations. The abstracts of the NASA Remote Sensing of Earth Resources Programs were searched and yielded more than 20 additional citations. The Government Research Abstracts yielded 8 citations.

The Directory of Fire Research in the United States, 1967-1969, 5th Edition, was a valuable source of information for subject matter, organizations, and personnel involved in the various aspects of fire research (including forest fires). Later, the earlier editions of the Directory as well as the latest 6th edition (1969-71) were searched.

Environmental Science and Technology and the Air Pollution Control Association journals were searched as well as the preprints of papers presented at various American Chemical Society -- Division of Water, Air, and Waste Chemistry meetings.

The resources of The John Crerar Library, the IIT Library, and the Chicago Public Libraries were also searched. More than 300 forestry management and forestry research volumes were identified, but less than 15 of these were judged to be useful to the program.

The Chicago Office of the Government Printing Office was visited. The current resources were examined and four summary type publications were acquired. These identified other personnel active in fields related to the project scope.

Abstracts, citations, journal articles, and microfiche were obtained. These were screened and catalogued for use in developing the emission factors.

Efforts were then concentrated on acquiring published and unpublished material. These published materials were to be found in symposias, proceedings, meetings, and conferences relating to the subject area of interests. The unpublished materials were those given at talks, data taken but not formally published, data in the process of being published, or data presently being taken.

The visit to the Forest Products Library and the libraries of the University of Wisconsin Forestry and Agriculture Departments in Madison, Wisconsin, was very productive. The

Forest Products Library yielded about 10 new references, including pyrolysis data and an excellent report from the Rand Corporation, entitled "The Simultaneous Flammability of Wildland Fuels in the United States". This work contains the construction of two "growth stages dependent" burning indices, a calculation of the national distribution of wildland fuels, and an evaluation of them.

Over 433 primary abstract cards (references) were prepared. These abstracts were descriptive of the best available literature pertinent to the program. Some of these references were bibliographies and thus indicated a larger number of source materials for information. Following an initial screening of the abstract cards and/or the documents they represented, photocopies, microfiche, or original hard copies were obtained of 154 of them. These materials were secured from the John Crerar Library, IITRI resources, The Forest Products Laboratory, The Government Printing Office, The University of Illinois Library, and the EPA.

A special area of potential interest was the capability of using remote sensing in forest fire emission studies. Thus, references to organizations in the field of remote sensing were obtained from work done on Contract NASW-2173, Survey for Air Pollution Monitoring Instrumentation, IITRI Project C6246.

From the formal published literature, personnel known to be active in the field were documented and categorized into groups based on their degree of involvement in the study of atmospheric emissions from forest fires. The author index of the source documents and abstract cards that were prepared were analyzed to uncover the organization and structure of the research. A plot of the number of authors who had written papers of interest, versus the number of papers selected for each author, illustrated the diversity of the field as well as the intensity of activity. From this analysis and from consideration of the subject areas of the papers, a list of primary contacts and secondary contacts were prepared. These contacts were utilized in preparing site visits on the planned survey trips.

The services of the Air Pollution Technical Information Center at Research Triangle Park, North Carolina, was utilized in the early phase of the program to obtain pertinent abstracts and later, near the end of the program, to obtain material abstracted during the interim period. Information was also requested from the Library of Congress, Science and Technology Division, National Referral Center, Washington, D.C.

Trade industry groups were contacted for information and leads to personnel working in the area of emissions from forest fuels combustion.

2.2 Site Visits

From the pre-project information search, the locations of personnel knowledgeable in the areas of forest fire behavior and emissions were determined. These people were found to be either employed with schools of forestry or environmental science. Coincidentally, the analysis of author and source documents reinforced the selection of people to contact and visit. In addition, the close proximity of a university to a Forest Service facility was fortunate, in that these site visits could be arranged with a minimum of time delays.

The U.S. Forest Service maintains strategically located offices, research units, regional forestry headquarters, and three forest fire laboratories. These specialized fire laboratories are: Northern Forest Fire Laboratory, Missoula, Montana; Forest Fire Laboratory, Riverside, California; and the Southern Forest Fire Laboratory, Macon, Georgia. Arrangements were made to talk to staff members at each fire laboratory because each laboratory has a different fire-related mission. Thus, three survey trips were taken to interview people in the Rocky Mountain area, Pacific area, and the Southeastern area.

The site visits were very fruitful. The discussions with personnel active in the area of forest fires and air quality resulted in information, literature, and suggestions directly applicable to the objectives of the project. Demonstration burns, with concurrent emission testing, were also witnessed at the Southern Forest Fire Laboratory and at the University of California-Riverside.

2.3 Letters and Telephone Calls of Inquiry

As the information search progressed, telephone calls were made for information or for clarification of information. The responses obtained were excellent. They primarily consisted of suggestions for further research, information on publications, and referrals to other persons knowledgeable in the project area.

Various letters were written to obtain specific information that would not have been available in the open, formal publication services. This was especially important in obtaining information on fuel assessments from experienced professionals.

Inquiries were made to firms with the capabilities of remote sensing of pollutants. For example, Environmental Measurements, Inc. (San Francisco, California) was very enthusiastic about the project and tried to get some data on their Cospec II instrument. This firm is the U.S. licensee of the Barringer Correlation Spectrometer that has been utilized in the measurement of some of the airborne pollutants (SO_2 and NO_2) in the atmosphere. Unfortunately, the availability of the instrument and the convenience of an accessible forest fire could not be programmed for an experimental test.

2.4 Contributors

Personal contacts were very helpful in obtaining publications, references, and names of other people to contact. An "inverted pyramidal effect" took place, in that all the leads on emission studies from forest fuels eventually led to personnel working in the laboratories in the Northwest, California, and Southeast of the United States.

Since the U.S. Forest Service has recognized the assessment of fuel in its new scheme of fire control, fuels specialists were available in each geographic area of the country. These sources were then contacted for data contributions.

A list of the names of the people who generously contributed their time and knowledge to this project is given in Appendix A.

3. ACREAGE BURNED

3.1 Wildfire

The wildfire acreage burned has been the most accurate estimate of the information needed to obtain more reliable pollutant emission values from forest fires. The Division of Cooperative Forest Fire Control of the Forest Service-U.S. Department of Agriculture has prepared a compilation of wild fire statistics for the United States. This publication has been utilized to obtain acreage consumed per geographic area. No comparable set of statistics are available for managed burn acreage, since reporting requirements vary among state agencies and other federal agencies, such as the Bureau of Land Management, National Park Service, Fish & Wildlife Services, Bureau of Indian Affairs, and the Tennessee Valley Authority. Also, a clarification in nomenclature must be made between various types of managed burning such as controlled burning, prescribed burning, slash burning, agricultural burning, range rehabilitation, litter removal, etc.

Tables 1 and 2 together constitute a summary and compilation of data on the number of wild fires and acres burned to size classes of fire from the "1971 Wild Fire Statistics", USDA Forest Service, 1972 (13).

3.2 Managed Fires

Managed fires are intentionally initiated for a variety of purposes, objectives, and benefits. One form of managed fires, prescribed burning, is based on the premise that fire is natural and can be used as a valuable and essential management tool. Fire is used only when and where it is needed, by controlling and managing it in such a way that it has beneficial effects for the user. Prescribed fire is defined by the Society of American Foresters as:

> "The skillful application of fire to natural fuels under conditions of weather, fuel moisture, soil moisture, etc., that will allow confinement of the fire to a predetermined

Table 1

SUMMARY OF WILDFIRE STATISTICS FOR THE UNITED STATES -- CALENDAR YEAR 1971 FOR PROTECTED AREAS, BY GROUPS OF STATES (13)

		FOREST AREA 1/ 2/				NUMBER OF FIRES					AREA BURNED					BURNED PORTION OF FOREST AREA	
GROUPS* OF STATES	OWNERSHIP 4/ 3/	Needing Protection	Pro-tected	Unpro-tected	Percent Protected	TOTAL	Protected Area		Unprotected Area		TOTAL	Protected Area		Unprotected Area		Pro-tected	Unpro-tected
		M Acres	M Acres	M Acres	%	Number	Number	%	Number	%	Acres	Acres	%	Acres	%	%	%
UNITED STATES	Federal	712,231	646,694	65,537	90.80	13,167	13,167	100.00	No Data	N.D.	1,719,315	1,719,315	100.00	No Data	N.D.	0.27	N.D.
	State & Private	613,971	574,443	39,528	93.56	95,231	[illegible]	96.26	3,558	3.74	2,559,157	1,826,580	71.37	732,577	28.63	0.32	1.85
	TOTAL	1,326,202	1,221,137	105,065	92.08	108,398	[illegible]	96.72	3,558	3.28	4,278,472	3,545,895	82.88	732,577	17.12	0.29	0.70
ROCKY MOUNTAIN GROUP	Federal	297,596	297,598	---	100.00	7,362	7,362	100.00	---	---	539,538	539,538	100.00	---	---	0.18	---
	State & Private	156,435	133,340	23,095	85.24	6,706	6,156	91.80	550	8.20	234,867	224,942	95.77	9,925	4.23	0.17	0.04
	TOTAL	454,033	430,938	23,095	94.91	14,068	13,518	96.10	550	3.90	774,405	764,480	98.72	9,925	1.28	0.18	0.04
PACIFIC GROUP	Federal	385,593	320,056	65,537	83.00	3,859	3,859	100.00	---	---	1,123,684	1,123,684	100.00	---	---	0.35	---
	State & Private	66,574	63,522	3,052	100.00	5,436	5,436	100.00	No Data	N.D.	39,044	39,044	100.00	No Data	N.D.	0.06	---
	TOTAL	452,167	383,578	68,589	84.83	9,295	9,295	100.00	---	---	1,162,728	1,162,728	100.00	---	---	0.30	---
NORTH CENTRAL GROUP	Federal	10,253	10,253	---	100.00	450	450	100.00	---	---	14,979	14,979	100.00	---	---	0.15	---
	State & Private	79,820	76,126	3,694	95.37	11,382	9,717	85.37	1,665	14.63	217,770	115,270	52.93	102,500	47.07	0.15	2.77
	TOTAL	90,073	86,379	3,694	95.90	11,832	10,167	85.93	1,665	14.07	232,749	130,249	55.96	102,500	44.04	0.15	2.77
SOUTHERN GROUP	Federal	16,143	16,143	---	100.00	1,413	1,413	100.00	---	---	40,419	40,419	100.00	---	---	0.25	---
	State & Private	234,624	224,937	9,687	95.87	58,744	57,401	97.71	1,343	2.29	1,951,920	1,331,768	68.23	620,152	31.77	0.59	6.40
	TOTAL	250,767	241,080	9,687	96.14	60,157	58,814	97.77	1,343	2.23	1,992,339	1,372,187	68.87	620,152	31.13	0.57	6.40
EASTERN GROUP	Federal	2,644	2,644	---	100.00	63	63	100.00	---	---	695	695	100.00	---	---	0.03	---
	State & Private	76,518	76,518	---	100.00	12,963	12,963	100.00	---	---	115,556	115,556	100.00	---	---	0.15	---
	TOTAL	79,162	79,162	---	100.00	13,026	13,026	100.00	---	---	116,251	116,251	100.00	---	---	0.15	---

1/ Federal land areas shown as Needing Protection, Protected and Unprotected, are taken from Official Reports submitted by the reporting Federal Agencies.
2/ Includes an estimated 407,338 M acres nonforest watershed land, as reported by the various State & Federal Agencies.
3/ State and privately owned land areas shown as Protected are under the [illegible] of the Clarke-McNary (C-M) Cooperative State and Federal Fire Control Program.
4/ Protected Federal land areas shown are under the protection of the following Federal Agencies: U.S. Forest Service, Bureau of Land Management, National Park Service, Fish and Wildlife Service, Bureau of Indian Affairs, and the Tennessee Valley Authority.
5/ Alaska [illegible] will [illegible] periodically as land is selected under the Statehood Act.
6/ State and private [illegible] needing protection revised by Official State Report
7/ [illegible] private land [illegible] acreage not included in 1965 Area & Cost Study

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Table 2

COMPILATION OF DATA RELATED TO SIZE CLASSES OF FIRE - 1971 (13)

1) Geographic Groups of States	Rocky Mountain	Pacific	North Central	Southern	Eastern	United States
2) Listing of Regions within Group	a) Northern, b) Rocky Mountain, c) Southwestern d) Intermountain	a) California b) Alaska c) Pacific Northwest	North Central	Southern	Eastern	
3) Listing of States within (1) and (2)	a) Idaho, Montana, N. Dakota b) Colorado, Kansas, Nebraska, South Dekota, Wyoming c) Arizona, New Mexico d) Nevada, Utah	a) California, Hawaii b) Alaska c) Oregon, Washington	Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, Ohio, Wisconsin	Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, Oklahoma, South Carolina, Tennessee, Texas, Virginia	Connecticut, Delaware, Main, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, West Virginia	
4) Number of Fires (CY-1971)	14,088	9,295	11,832	60,157	13,026	108,398
5) Area Burned (acres) (CY-1971)	774,405	1,162,728	232,749	1,992,339	116,251	4,278,472
6) Number of Wildfires by Size Classes (Protected Area Only) (CY-1971)						
Size Classes						
A - 0.25 acres or less	7,647	7,168	2,669	7,729	5,277	30,490
B - 0.26 to 9 acres	4,191	1,556	5,572	37,886	6,626	55,831
C - 10 to 99 acres	1,237	361	1,698	11,682	971	15,949
D - 100 to 299 acres	215	84	185	1,071	106	1,661
D - 300 to 999 acres	147	52	35	318	35	587
F - 1,000 to 4,999 acres	74	41	7	100	10	232
G - 5,000 acres or more	27	33	1	28	1	90
7) Acres Burned by Wildfires by Size Classes (Protected Area Only) (CY-1971)						
Size Classes						
A - 0.25 acres or less	124	56	55	8	155	398
B - 0.26 to 9 acres	12,414	3,527	15,006	188,897	13,400	233,244
C - 10 to 99 acres	39,736	13,572	49,933	342,986	25,817	472,044
D - 100 to 299 acres	37,455	14,266	28,904	170,123	18,124	268,872
E - 300 to 999 acres	91,741	29,014	18,793	163,273	16,607	319,428
F - 1,000 to 4,999 acres	183,565	97,733	8,238	194,522	21,148	505,206
G - 5,000 acres or more	399,445	1,004,560	9,320	312,278	21,000	1,746,703

> area, and at the same time will produce the intensity of heat and rate of spread required to accomplish certain planned benefits to one or more objectives of silviculture, wildlife management, grazing, hazard reduction, etc. Its objective is to employ a fire scientifically to realize maximum net benefits at minimum damage and acceptable cost."

Managed burning is used as a simulated "ecological" or "natural" fire control method. The periodic low intensity surface fires kept the forest free of debris, unwanted understory trees, and minimized high intensity crown fires by removal of the ground litter (fuel accumulation). The use of managed fires has been expanded and applied to natural fire risk areas, other fuel types, and management practices.

From the point of view of the purist, debris burning, such as slash burning after clear-cutting, agricultural burning, railroad and road right-of-way burning, orchard prunings, etc., have not been considered prescribed burnings.

In the South, managed burning is widely used for hazard reduction, insect and disease control, site preparation, slash disposal, wildlife habitat management, and to improve recreational value. In the West and Southwest brush control for range rehabilitation and management, hazard reduction, and watershed improvement are some of the purposes of managed fires (14,15,16).

4. FUELS, FUEL TYPES, AND ESTIMATED QUANTITIES

The combustion of wood is a continuing study on a theoretical, as well as an applied basis. These studies have been based on beneficial or deleterious effects, depending on the outlook of the viewer. At present, the mechanism and chemistry of wood combustion, especially of forest fuels, is still considered a complex phenomenon.

The U.S. Forest Service considers the assessment of fuel to be of major importance and each district measures standing timber and fuels. The present mission of the Rocky Mountain Forest & Range Experiment Station is the development of the National Fire Danger Rating System (NFDR) (17). The NFDR system uses fuel models to develop fire behavior components to aid in planning fire control activities. Fuel models were devised (18) to organize fuels information as inputs for solution of a fire spread model. The fuel models in the NFDR system are concerned with ignition, and thus only those fuels involved in combustion within the immediate flame front are considered (19). The length of the flames at the head of the fire was assumed to be directly related to the contribution that fire behavior makes to the job of containment.

The fuel loading as it relates to the various fuel models will be correlated to regional forest cover types, timber types, or fuel types.

However, for air quality assessment, fuel loadings will require adjustments to obtain total material consumed by a wildfire (% burned). As a first approximation, the fuel loadings designated in the NFDR fuel model will be totally consumed in a wildfire. Some foresters feel that fuel models and emissions can be related. Thus, a continuing study of this relationship may lead to better fire management and emission output.

4.1 General Forest Fire Background

In the United States, the forested area comprises approximately 786 million acres or 34.4% of the land area. Forest fires are quite prevalent and usually seasonal for certain geographical areas. The U.S. Forest Service has conducted research for many years on free-burning forest fires under real as well as simulated natural conditions. Fires that sweep through the forest usually do not destroy all the trees. Many variables are inherent and characteristic of a forest fire. The topography or terrain of the forest, the vegetation composing the forest, and the atmosphere above the forest are well interrelated to the burn rate and spread, intensity of burn, and the size of the burn. These variables may be altered by fire suppression and control technology, with the possibility of increased emission of combustion by-products.

Large forest fires produce great volumes of smoke which vary in character and color in accordance with variation in fuels (vegetation) and rates of combustion. The main smoke column, if present, exhibits an almost continuous corkscrew motion, but at the base, variation in smoke color and density occurs due to the variation in intensity and type of combustion of the fuel supply.

Of the major North American forest fires, the worst was the Peshtigo Fires in Wisconsin and Michigan in 1871 when 3,780,000 acres of timber were burned. The Dudley Lake Fire, Arizona, in a 48-hour period consumed 20,000 acres of mature timber and slash which approximated 300,000 tons by weight. At the peak period, about 22,500 tons of dry weight were consumed per hour. The Sundance Fire (20) in northern Idaho in the summer of 1967 was one of the better documented forest fires. The convection column reached an altitude of 31,000 ft, traveled 16 miles in 9 hours and consumed over 50,000 acres of mature trees, ground litter, brush, and crown material.

Meteorological, topographical and fuel determinations were carefully analyzed to study the fire behavior characteristics.

Historically, men and materials have been utilized for prevention, suppression, and control of forest fires rather than the measurement of pollutant parameters. We hope that time will modify these efforts enough to obtain a more complete knowledge of the total picture of a forest fire.

4.2 Overview of Fuels and Fuel Types

The importance of fuel type on the fire process and the emissions therefrom cannot be overestimated. Therefore, categorizing forest regions by fuel types was an essential task of the program. Historically, the geographic distribution of forest trees has been made by botanists, and thus the forested areas were grouped in vegetation zones. The Society of American Foresters' booklet (21) names forest types from the predominant stand of trees. They recognize 106 forest type groups in the eastern part of North America and 50 type groups in the western part. The U.S. Forest Service classifies forest types into several major type groups; 10 Western and 10 Eastern. The classification stresses the commercial value of forest cover types. The American Forest Institute, a trade group of forest products industries, have produced a full color educational map of the United States outlining geographic areas and their related three coverage. This map is appendixed to this report, Appendix D.

Shroeder (22) divided the country into homogeneous areas based on the combination of fire-climate and fuels. This was the first instance of a distribution pattern which was based on natural forces rather than one of taxonomic, topographical, or political demarcation of an area. Komarek (9) has also proposed seven lightning, bio-climatic regions for North America. Recently, Fahnestock (23) characterized forest fuels using two keys: the fire spread potential and the crowning potential. The keys are easily recognized and evaluated in the field and can be used by persons without technical knowledge of vegetation or experience with fire. Color photographs are used to illustrate descriptions used in evaluating the vegetation in terms of using the keys.

During a study of the biological and environmental consequences of nuclear war, The Rand Corporation (24) made a study of the possible extent of wildland fires that might result from a large scale nuclear attack. A simultaneous natural fuel condition for the entire nation was considered and for this purpose an assessment of the national wildland flammability conditions were needed. Utilizing Küchler's map and description, "Potential Natural Vegetation of the Coterminous United States", 1964, a national wildland fuel distribution data summary was prepared by reducing all wildland vegetation to 15 fuel types. This study is potentially of great value but at the moment not related and pertinent to the project.

A few regions in the U.S. Forest Service have a fuel classification system. An example is the Region 6 Guide for Fuel Type Identification, 1968 (25). Each fuel-type is defined by one of four rate-of-spread and one of four resistance to control classes, or a possible 16 combinations. Black and white photographs of examples of typical fuel types in the region are included for reference. However, no estimates of fuel loadings by size class in tons per acre are included.

4.3 Fuel Models

A new, country-wide fuel identification system is presently being developed. This system will attempt to include estimates of fuel loading by size class, in tons per acre. The Director of the Division of Forest Fire and Atmospheric Science Research of the U.S. Forest Service states (26) that research in fuel science has recently developed descriptive fuel models for use in all forest regions.

Rothermel introduced the concept of fuel models tailored to the vegetation patterns in the field (18). The fuel model is a simulated fuel complex for which all the required fuel descriptors have been determined and describes the vegetation pattern on the basis that fuels have inherently similar characteristics. The fuel model would then represent typical field situations. A knowledge of the characteristics of the fuels in the field appears basic to a study of fire behavior. Eleven fuel models have been assembled to represent forests, brush, and grasslands found in the temperate climate of North America. Refinements of the models could be made for more specific fuel situations. The input parameters for the fuel models were grouped on the basis of current knowledge of mechanisms of fire spread and the propagation of a fire. Table 3 is Rothermel's (18) values for the National Fire Danger Rating System.

The environmental parameters of wind, slope, and expected moisture changes were superimposed on the fuel model and incorporated into a National Fire Danger Rating System (NFDR) (17,19). The NFDR System considers five classes of fuels, three dead and two living. These fuels were selected on the basis of combustibility; response to moisture for the dead fuels (1-hr, 10-hr, and 100-hr timelag class) and whether the living fuels were herbaceous or woody. For this project, the goal and purpose of the NFDR which is the rating of fire danger (prediction of the behavior of a potential fire) is of value in its relation to the development of a uniform national estimate of fuel models and loadings in tons per acre.

The previous sections give various methods or systems of identifying the fuel types and also fuel loadings for various fuel models. These have been included to indicate the development of the importance of understanding the role of fuels in the total forest fire behavior from point of ignition, spread and extinction, and the overall production of emissions in the process.

Table 3

VALUES FOR INPUT PARAMETERS OF 11 PRELIMINARY FUEL MODELS FOR THE NATIONAL FIRE DANGER RATING SYSTEM[1] (18)

Fuel types	Total loading	Dead fuel						Living fuel		Fuel depth
		Fine		Medium		Large				
		σ	w_o	σ	w_o	σ	w_o	σ	w_o	
	Tons/acre	*Ft.*$^{-1}$	*Lb./ft.*^{2}	*Ft.*$^{-1}$	*Lb./ft.*^{2}	*Ft.*$^{-1}$	*Lb./ft.*^{2}	*Ft.*$^{-1}$	*Lb./ft.*^{2}	*Ft.*
Grass (short)	0.75	3,500	0.031	--	--	--	--	--	--	1.0
Grass (tall)	3.0	1,500	.138	--	--	--	--	--	--	2.5
Brush (not chaparral)	6.0	2,000	.046	109	0.023	--	--	1,500	0.092	2.0
Chaparral	25.0	2,000	.230	109	.184	30	.092	1,500	.230	6.0
Timber (grass and understory)	4.0	3,000	.092	109	.046	30	.023	1,500	.023	1.5
Timber (litter)	15.0	2,000	.069	109	.046	30	.115	--	--	0.2
Timber (litter and understory)	30.0	2,000	.138	109	.092	30	.230	1,500	.092	1.0
Hardwood (litter)	15.0	2,500	.134	109	.019	30	.007	--	--	0.2
Logging slash (light)	40.0	1,500	.069	109	.207	30	.253	--	-	[illegible]
Logging slash (medium)	120.0	1,500	.184	109	.644	30	.759	--	--	2.3
Logging slash (heavy)	200.0	1,500	.322	109	1.058	30	1.288	--	--	3.0

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[1] For all models, $h = 8{,}000$ B.t.u./lb., $\rho_p = 32.0$ lb/ft^3, σ, fuel particle surface area-to-volume ratio, 1/ft.

W_o, ovendry fuel loading, lb/ft^2

h, fuel particle low heat content, B.t.u./lb.

ρ_p, ovendry particle density, lb/ft^3.

4.4 Quantity of Fuel Consumed-Burned

Many descriptors have been used to describe forest fuels. The terminology and concept of fuel loading (quantity of fuel in a defined area) in relation to fuel consumption by fire is at present not firmly and clearly defined. This difficulty has tended to cause confusion even among forestry personnel. In this report, fuel loadings have been reported as estimates of the tonnages of fuel that will be consumed in an average wildfire.

The intensity of the wildfire can be approximately scaled by experienced observers; for example, light surface fire consuming only the top litter layer; brush fire consuming most of the litter and brush; to very high tensity fires and crown fires burning off all litter, fire fuel particles, and the entire organic soil mantle. However, even in the most intense fire, the greater proportion of the larger woody material will not be consumed. The larger fuels do not contribute to fire intensity or to the rate of spread since these burn after the main fire front has passed and are difficult to extinguish.

In this report, the stated estimated fuel loadings will be synonymous to the "available fuel" (fuel which will be consumed in a wildfire under a given set of or prevailing weather conditions). "Total fuel" has been defined in different ways by forestry personnel to indicate the complete consumption of the fuel. "Total fuel" will be defined in this report as all the combustible material that would burn under the most severe weather and burning conditions. "Potential fuel" would then be all the larger woody material that is referred to as fuel, but remains even after an extremely high-intensity wildfire.

The U.S. Forest Service is the single organization administering the largest forest acreage, over 187 million acres in 41 states and Puerto Rico. Since they are responsible for the reporting, compiling, and publication of forest fire statistics, their system of fuel identification and assessments will be utilized in this report.

The various methods of fuel identification are of value only when they are related to the existing fuel quantity, the quantity consumed by the fire, and finally the geographic area and conditions in which the fire occurred. These relationships are discussed in the following sections.

4.5 Regional Values of Fuel Loadings

Since the U.S. Forest Service Regions are in the process of assessing fuel, a more reliable fuel inventory should be forthcoming. Eventually, the fuel loadings should reflect the breakdown given for acreage burned by states as in the compilation on "Wildfire Statistics" (13).

The U.S. Forest Service has nine National Forest Regions. Fuel loadings for these regions as well as fuel loadings for smaller geographic areas were obtained where these values were reported in the literature.

4.5.1 Region 1, Northern Region

The Northern Region covers Montana, northeastern Washington, northern Idaho, North Dakota, and northwestern South Dakota. This region has 16.8 million acres of commercial forest land of which 7 million acres have a cover type dominated by pine (western white pine, ponderosa pine, and lodgepole pine). Other general tree types in this northern Rocky Mountain forest are western larch and Engelman spruce. Beaufait (27) refers to a study by Bray and Gorham (1964, p 106) that the organic mantle is enriched at the rate of 3 to 4 tons per acre per year in the North Temperate Zone. The decomposition rate of organic matter is much less than the production rate as compared with the Tropical Zone. Thus, fuel accumulates in this region to a hazardous level unless fire removes it.

Research studies conducted on logged areas in western Montana (western larch-interior Douglas-fir type) indicated that the weight of logging debris and residual debris (dead and down material, including duff on the site before logging) ranged from 50 to 150 tons per acre, averaging just over 100 tons of organic matter per acre (28). The atmospheric emissions from burning logging and residual debris depends on how it is burned. Slash pile burning results in relatively complete removal of the debris. Broadcast burning, i.e., burning the slash where it fell rather than gathering it in piles, reduces the fire hazard by removal of the "fine fuels" but leave considerable material that makes reforestation difficult (11). In another study (29) at the University of Montana, Missoula County, Montana, the total organic matter of Douglas fir slash, non-commercial residue, and duff (after logging) averaged 64 tons per acre.

Region 1 does not have a guide for fuel type identification but does have estimates of available organic residues. The region does have acreage and biomass information available in their files which could be assembled for use at a later date. Unpublished data at the nearby Northern Forest Fire Laboratory would also be accessible (30).

An average fuel loading of 60 tons per acre can be estimated for this region.

4.5.2 Region 2, Rocky Mountain Region

The Rocky Mountain Region covers Colorado, Kansas, Nebraska, South Dakota, and Wyoming and encompasses approximately 22 million acres of forest land. The following is a broad, subjective estimate of fuel loadings by type, from readily available information (31).

Region 2 has not prepared a "Guide for Fuel Type Identification". An average fuel loading of 30 tons per acre can be estimated for this region.

Fuel Types Based on the National Fire Danger Rating System	Estimated Acres in Fuel Type	Tons/Acre of Vegetative Matter
Unburnable	1,000,000	- - -
Fuel Model A	2,500,000	1-3 tons/acre
Fuel Model C	7,800,000	20-40 tons/acre
Fuel Model G	4,800,000	50-100 tons/acre
Fuel Model H	5,000,000	100-150 tons/acre
Others	900,000	5-20 tons/acre

4.5.3 Region 3, Southwestern Region

The Southwestern Region covers Arizona and New Mexico. The following are approximate tonnages per acre in Region 3 (32) based on the National Fire Danger Rating System fuel models.

Fuel Model	Principal Vegetation	Approximate Tonnage of Fuel/Acre*
A	Grass and herbaceous plants	0.5
A	Grass, herbaceous plants and less than 1/3 pinyon pine, juniper or ponderosa pine	1.0
B	Chaparral	20.0
B	Coniferous slash with needles attached	100.0
C	Open ponderosa pine	8.0
C	Ponderosa pine	20.0
C	Pinyon pine or juniper	5.0
G	Spruce	20.0
H	Mixed conifer	50.0

A system to inventory fuels is being developed for the region.

* We interpret these values to be available fuel.

In Arizona, the forest area covers 20.6 million acres, of which 4 million acres consists of commercial forest. Ponderosa pine is the dominant timber type covering 92% of the commercial forest area. The pinyon-juniper and chaparral types cover 12.2 million and approximately 4.4 million acres, respectively. Of the commercial forest, ponderosa pine predominates on 3.66 million acres, Douglas-fir on 129,900 acres (3%), aspen on 79,000 acres (2%), and the rest consists of fir-spruce at the higher elevations (33).

In New Mexico, the forest area covers 18.2 million acres of which 6.3 million acres are commercial forest. Eighty-nine percent of the 11.9 million acres of non-commercial forest is classified as pinyon-juniper type and the rest is chaparral (oak brush and woodland). Ponderosa pine type occupies 4.3 million acres (69%) of the commercial forest area, Douglas-fir type on 1 million acres (16%), fir-spruce type on 525,000 acres (8%), and aspen type on 367,000 acres (6%) (34).

The forest floor is an important fuel component. Ffolliott, et al. (35), obtained depth, weight, and density of the forest floor under Ponderosa pine in Arizona. They obtained a mean depth of 1.3 inches, mean weight of 9.3 tons per acre, and a mean density of 6.0 tons per acre-inch. The bulk of the weight was in the H layer (7.3 tons per acre).

Litter production under chaparral in central Arizona was measured by Pase (36). The chaparral community produced an annual litter mass of 215.3 gm/m^2 in northerly slopes and 193.2 gm/m^2 in southerly slopes. Leaves comprised the greatest percent of annual litter shed; for example, 100% of the leaves on healthy shrub live oaks were replaced each year. The forest floor varied from 4.1 to 12.1 tons per acre.

Besides knowing the average amount of fuel on the forest floor, a measure of the amount of fuel consumed in a moderately high intensity surface fire would indicate the approximate amount of consumable material. Davis, et al. (37), described a prescribed burn that took place in the Coconino National Forest in northern Arizona. Duff weights were an average of 10.2 tons per acre in a flat area and 17.6 tons per acre in a sloped area. Burning resulted in 3.4 tons per acre consumed in the flat area and 6.3 tons per acre in the sloped area. Besides the 30% slope, the area with 17.6 tons/acre had a 5% higher air temperature and 2 miles per hour higher wind.

Since chaparral, or evergreen brush, covers about 8% of the total area of Arizona, wildfire in such an area can be potentially very extensive. Fosberg and Davis (38), and Lindenmuth and Davis (39), summarized and interpreted the first research study of fire behavior in Arizona oak chaparral, in the vicinity of Prescott, Arizona, in the Prescott National Forest.

CHAPARRAL FUEL DATA (38)

		Low	Mean	High
Loading, tons/acre	Leaves	0.3	2.1	6.2
	Total	5.0	13.9	34.8
Surface area/vol., in^{-1}	Leaves	1918	2519	3314
	0-1/8"	--	5102	--
	1/8-1/4"	--	1915	--
Litter bed depth, inches		2.42	2.81	3.58

SHRUB LIVE OAK CHAPARRAL (38)

Total loading before burn	0.633 lb/ft^2
Total consumed by fire	0.407 lb/ft^2
Flaming combustion	0.287 lb/ft^2
Glowing combustion	0.120 lb/ft^2

% FUEL LOADING BY CLASS (38)

Total	0.637 lb/ft^2	100%
less than 1/4"	0.325 lb/ft^2	51
1/4"-1"	0.115 lb/ft^2	18
over 1"	0.102 lb/ft^2	16
leaves	0.095 lb/ft^2	15

The fire season in the southwest is May and June and sometimes August to September. The problem areas are chaparral, ponderosa pine, and lodgepole pine. An average fuel loading of 10 tons per acre can be estimated for this region.

4.5.4 Region 4, Intermountain Region

The Intermountain Region covers Utah, southern Idaho, western Wyoming, and Nevada. Qualitative data is not readily available (40). The Northern Forest Fire Laboratory in Missoula, Montana, was referred to as a location for information and data relative to forest fuels in the Intermountain area.

Utah's forested area is 14.9 million acres, of which 4 million acres are commercial forest. Of the non-commercial forest, 9.3 million acres or 86% is classed as pinyon-juniper type, and 1 million acres as mountain brush (Gambel oak). Aspen (33%) and fir-spruce (25%) are the largest timber types in the commercial forest. Others are Douglas-fir, lodgepole pine, and ponderosa pine (41).

The nearest fuel loading estimates that can be utilized is based on Region 3's data.

Pinyon-Juniper	9.3 million acres	5 tons/acre
Mountain Brush	1.0 million acres	8.8 tons/acre
Other Non-Commercial	0.6 million acres	5 tons/acre
Aspen	1.3 million acres	12-20 tons/acre
Fir-Spruce	1.0 million acres	20 tons/acre
Other Conifers	1.7 million acres	8-20 tons/acre

An average fuel loading of 8 tons per acre can be estimated for this region.

4.5.5 Region 5, California Region

This region covers the states of California and Hawaii. The fuel models developed for the National Fire Danger Rating System are used to describe the forest fuels. The tonnage figures furnished by the NFDR project are used for most purposes. Therefore, adjustments must be made to the NFDR tonnage figures to obtain a better estimate of the total material available and the total consumed. In Region 5, the available fuel models do not describe the fuel types accurately, especially in uneven aged timber stands with significant amounts of logging debris which have not been disposed of or treated (42).

Fuel Model & Name		Tonnage Per Acre*
A	Grass	3
B	Brush	19
C	Open Pine Timber	
	West side of Sierra Nevada Mountains	20 + (20) = 40
	East side of Sierra Nevada Mountains	11 + (9) = 20
D	Young Brush	12
G	Dense Conifer	30 + (50) = 80
I	Logging Slash **	
	Light	30
	Medium	35 - 70
	Heavy	80 - 150

* We interpret these values to be available fuel.
** California Region Estimate.

The figures within the parenthesis in the above tabulation were Region 5's estimates of the additional tonnage consumed in a wildfire of the fuel types. Fuel Model B was not used for logging slash (NFDR System). Fuel Model C or D was used so that the significant differences between the fire behavior in chaparral (Model B) and conifer stands could be exhibited. Little or no use was made of Fuel Models E, F, or H in Region 5 (42).

One-half of California is covered by vegetation; coniferous forest, woodland savanna, chaparral, and grassland. It is estimated that 15-24 million acres of brush (of which 8 million acres are chaparral) exist in California. The fire potential is tremendous, in that living fuel in drought conditions can act like dead fuels in combustibility.

Countryman (43) refers to studies conducted on certain chaparral fuels in southern California. In that study, plots of chaparral (fuel) were dissected to obtain amounts and distribution of fuel particles within the fuel bed. Results from typical plots in three different chaparral weights were given and reproduced in Tables 4, 5, and 6.

Kilgore (44) made a study of managed burning on a Sequoia-mixed conifer forest in Kings Canyon National Park, in which the white fir is the dominant tree in density. Before burn, there were 50 tons/acre of total litter and duff fuel. After burn, there was a 75% reduction in litter fuels and 85% reduction in duff fuels. Remaining after the burn was 7.7 tons/acre. The estimated log fuel weights (understory trees) decreased from 12.8 to 2.8 tons per acre.

In the California region, the potential hazards from wildfire due to fuel accumulation have appeared in the newspapers and national weeklies. The hazard developed as a direct result of the extremely cold winter (1972-73) in the California Bay Area (Berkeley) which killed and injured 2-3 million Eucalyptus trees (approximately 3,000 acres)

Table 4

COMPOSITION OF LIGHT CHAPARRAL FUEL TYPE (43)

Item	Dry weight (tons per acre)	Percent of class weight
Total fuel:		
Living	2.19	17.6
Dead	4.10	33.0
Duff and litter	6.13	49.4
Total	12.42	--
Predominant species:		
California sage (*Artemisia californica*)	0.59	9.4
White sage (*Salvia apiana*)	4.45	70.7
Deerweed (*Lotus scoparius*)	1.25	19.9
Height (feet):		
Over 6	.00	.0
4 - 6	.02	.3
2 - 4	4.47	7.5
0 - 2	5.80	92.2
Size class:		
Flowers	.00	.0
Leaves	.76	12.1
Twigs to 1/4 in.	2.43	38.5
Stems 1/4 - 1/2 in.	1.45	23.1
Stems 1/2 - 1 in.	.98	15.6
Stems 1 - 2 in.	.76	10.7
Stems 2 in. or over	.00	.0

Table 5

COMPOSITION OF MEDIUM CHAPARRAL FUEL TYPE (43)

Item	Dry weight (tons per acre)	Percent of class weight
Total fuel:		
Living	9.76	46.1
Dead	5.32	25.2
Duff	6.06	28.7
Total	21.14	--
Predominant species:		
Chamise (*Adenostoma fasciculatum*)	11.02	73.0
Buckbrush (*Ceanothus cuneatus*)	3.02	20.0
Sumac (*Rhus laurina*)	1.05	7.0
Height (feet):		
Over 6	.92	6.1
4 - 6	2.90	19.2
2 - 4	5.09	33.7
0 - 2	6.19	41.0
Size class:		
Leaves	1.20	8.0
Twigs to 1/4 in.	3.80	25.2
Stems 1/4 - 1/2 in.	2.78	18.4
Stems 1/2 - 1 in.	5.51	36.4
Stems 1 - 2 in.	1.81	12.0
Stems over 2 in.	.00	.0

Table 6

COMPOSITION OF HEAVY CHAPARRAL FUEL (43)

Item	Dry weight (tons per acre)	Percent of class weight
Total fuel:		
Living	28.62	72.6
Dead	2.56	6.5
Duff	8.25	20.9
Total	39.43	--
Predominant species:		
Scrub oak (*Quercus dumosa*)	22.80	73.1
Buckbrush (*Ceanothus cuneatus*)	8.38	26.9
Height (feet):		
Over 6	7.96	25.5
4 - 6	8.46	27.1
2 - 4	11.42	36.7
0 - 2	3.35	10.7
Size class:		
Leaves	2.64	8.5
Twigs to 1/4 in.	4.04	13.0
Stems 1/4 - 1/2 in.	4.08	13.1
Stems 1/2 - 1 in.	4.45	14.3
Stems 1 - 2 in.	11.36	36.3
Stems over 2 in.	4.61	14.8

creating litter problems (as much as 50 tons of debris per acre) and potential wildfire problems with or without a hot, dry summer. A large part of the fuel produced by eucalypts is leaf litter which, in most forests, accumulates to about 1/2 to 1 ton per acre per year for at least 25 years (45). Additional fuel are the dead twigs, branches, and a unique fuel which is the dead bark that falls off in sheets and ribbons. Mount (46), as an Australian visiting silviculturist in 1969, viewed fires in the Berkeley area as a far greater threat than the San Andreas Fault. His observation of an ideal fire situation: a combination of topography, climate, vegetation, and houses buried in the vegetation (fuel accumulation under the eucalypts up to their stems, and a "perfect" intermixing of the fuels -- pine and eucalypts), leads him to foresee a catastrophe far worse than the Hobart fires of 1967 in Tasmania.

The annual accumulation of litter is a growing problem. Dodge (47) refers to a few studies in California. Accumulation rates of 0.45 to 1.3 tons per acre were found in the chaparral of southern California; 0.89 to 2.8 tons of litter per acre were contributed each year to the forest litter by several species in the central Sierra Nevada; and in studies of the giant sequoias (Sequoiadendron giganteum) groves, as much as 23 to 38 tons of dead fuel per acre were found. An average fuel loading of 18 tons per acre can be estimated for this region.

4.5.6 Region 6, Pacific Northwest Region

The Pacific Northwest Region covers the states of Washington and Oregon. This region has just completed a summary of the total acres for each fuel model (described in the National Fire Danger Rating System) found in this region. There is only a very small percent of National Forest land containing Fuel Models E, F, and H. Table 7 lists forest vegetation in the region and the acreage for

Table 7 - FUEL MODELS USED IN REGION 6 (48)
(Showing Acres in Each Model)

R6-6200-3 (9/67) UNIT	A	B	C	D	E	F	G	H	I		
01 DESCHUTES			276,400	1,155,700			403,200				
02 FREMONT	337,634	208,215	735,541	57,440	35,320						
03 G. PINCHOT		44,320					1,286,480		2,200		
04 MALHEUR	232,448	108,288	725,873				187,394				
05 MT BAKER							847,000		139,000		
06 MT HOOD							407,888		763,113		
07 OCHOCO	199,731		704,861				125,158				
08 OKANOGAN		40,000	150,455	548,637			1,082,883				
09 OLYMPIC				122,120		145,897	262,542	78,824	48,712		
10 R. RIVER O/C		195,000					489,498				
11 SISKIYOU O/C		393,024					727,746				
12 SIUSLAW							801,464				
13 SNOQUALMIE	3,870	14,570	136,515				993,536		98,688		
14 UMATILLA O/W	156,733	181,383	1,096,206				309,228				
15 UMPQUA			3,800				996,000				
16 W-WHITMAN	786,890	241,000	1,108,300				157,250				
17 WENATCHEE	202,907		531,200				1,211,098		51,275		
18 WILLAMETTE							1,485,000		215,000		
20 WINEMA	5,200		28,400	701,280			226,520				
TOTALS	1,925,413	1,425,800	5,497,551	2,585,177	35,320	145,897	11,999,885	78,824	1,317,988		

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each fuel model (48). This region does have a "Guide for Fuel Type Identification", 1968 (25), with black and white photographs of typical fuel situations.

An average fuel loading of 60 tons per acre can be estimated for this region.

Slash was broadcast burned in the Cascade Mountains of western Oregon and in the southern districts of Gifford Pinchot National Forest, Washington. The fuel data (49) was reported as follows:

Date	Acres Burned	Fuel Consumed, Tons
October 21, 1969	819	54,850
October 21, 1969	2,936	192,200
October 22, 1969	2,225	139,250
Total	5,980	386,300

The fuel burned averaged about 65 tons per acre.

4.5.7 Region 8, Southern Region

The Southern Region is composed of the following states: Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, Oklahoma, South Carolina, Tennessee, Texas, and Virginia. A regional guide for fuel type identification has not been developed. Table 8, a list of fuel types as it relates to the fuel models in the National Fire Danger Rating System, was available (50). The region was divided into 3 areas: Plains Area, Mountain Area, and Intermediate Area.

An average fuel loading of 9 tons per acre can be estimated for this region.

This region has developed the expertise on the use of fire to a highly sophisticated degree (51,52,53). Prescribed burnings as a pine management tool have resulted in numerous benefits, one of which has been the reduction of wildfires. In a 4-year study period, the number, size, and intensity of

All Plains Area Units (Except Florida)

Timber Type	Symbols	Fuel Models
Pine (except Sand Pine)	P	C,E,D
Bottomland Hardwood	BH	H
Pine & Hardwood	PH	E,H
Scrub Oak	ScO	D
Organic Soil	OS	Choose on the basis of the surface fuels in which the fire will spread
Grass	GR	A
Pocosin - High	Poc	B
Pocosin - Low	Poc	D

Florida

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Pine-LL-Slash Pine-Palmetto Flatwoods	PF	D
Pine-Longleaf-Scrub Oak	PLS	C
Pond Pine-Titi	PT	D
Sand Pine	SP	C
Sand Pine Double Burn	SPD	D
Pine-Hardwood	PH	E,H
Grass	GR	A
Sawgrass (Organic Soil)	GRO	C
Bottomland Hardwoods	BH	H
Cypress-Tupelo	CT	H

Mountain Area. All of the Chattahoochee, Cherokee, Ozark, Ouachita: Pisgah and Nantahala Units of North Carolina: Black Warrior, Bankhead, Shoal Creek and Talladega Districts of Alabama: The Andrew Pickens District of South Carolina.

Timber Type	Symbols	Fuel Models
Upland Hardwood	UpH	E,H
Conifers & Hardwoods	CH	E,H
Pine (all, except White Pine)	P	C,D,E
Pine Hdw. (except White Pine)	PH	E,H
Brush (Rhod., Laurel, etc.)	BR	F
Scrub Hardwood	ScH	E,H
White Pine		H

Intermediate Area. All areas not included in the Plains or Mountain Areas will fall in the Intermediate Area:

Timber Type	Symbols	Fuel Models
Grass	GR	A
Scrub Hardwoods	ScH	E,H
Pine (all)	P	C,D,E
Pine-Hardwood	PH	E,H
Pine Yaupon	PYO	H

All Areas	Symbols	Fuel Models
Slash (Clearcut) Pine		C
Slash (Thinning) Pine		D
Slash [illegible]		

Table 8. LIST OF FUEL TYPES - FUEL MODELS (50)

wildfires that occurred generally increased with increasing age of the fire protected forest. In the pine flatwoods of Georgia and Florida, wildfire burn percentage amounted to less than 0.1% with sound prescribed burning programs. With no prescribed burning, 7% of the forest acreage was burned during the same time period. In the South, fuel accumulation become hazardous when it exceeds about 3 tons per acre (54,55,56).

From the extensive studies and practice of prescribed burning in this region, the fuel loadings have been measured and reported in the literature (57,58,59,60). Managed fires (prescribed fires in the South) consume approximately 2 to 2.5 million acres with a fuel loading of 2 to 4 tons per acre (average of 3 tons per acre). In prescribed burning, the brushy fuel and the upper litter layers are the intended fire removal goal, and this is the portion of the fuel that is consumed.

In the central hardwoods area (Tennessee) the forest floor litter averages 4 tons per acre or about 1/5 the amount in a pine forest (61). The approximate composition of the litter is: hardwood leaves (64-74%), twigs (15%), grass (8%), and miscellaneous parts (3%).

4.5.8 Region 9, Eastern Region

The Eastern Region is composed of the following states: Connecticut, Delaware, Illinois, Iowa, Indiana, Maine, Maryland, Massachusetts, Michigan, Minnesota, Missouri, New Hampshire, New Jersey, New York, Ohio, Pennsylvania, Rhode Island, Vermont, West Virginia, and Wisconsin. This region is unique in that it covers two of the geographic groups of states in the United States (13), the Eastern and the North Central.

The information in Table 9 (62) is a broad classification of fuel models used in the Eastern Region National Forests. These fuel loadings, as defined in the NFDR System, are the

Table 9

FUEL MODELS (NFDR) IN THE EASTERN REGION (62)

	National Fire Danger Rating System Fuel Models			Approx. Avail. Fuel Loading, Total Tons	
Units	Primary	Secondary	Tertiary	Primary	Secondary
Allegheny	H			3.0	
Chequamegon	H	C		3.0	2.5
Chippewa	C	A		2.5	1.25
Clark	E			2.5	
Green Mountain	H			3.0	
Hiawatha	C	H		2.5	3.0
Huron-Manistee	C			2.5	
Mark Twain	E			2.5	
Monongahela	H	E		3.0	2.5
Nicolet	H	C		3.0	2.5
Ottawa	H			3.0	
Shawnee	E			2.5	
Superior	C	H	I	2.5	3.0
Wayne-Hoosier	E	C		2.5	2.5
White Mountain	H			3.0	
	Primary, Predominant Fuel Model.	May Occur, But in Minor or Scattered Areas.	Widely Scattered, Small, or Transition Types.		

estimated typical figures of the fuel that actually burns.

For this region, a very crude estimate of the fuel loading of a NE mixed conifers is 7 to 12 tons gross per acre of available fuel (the fuels consumed in a forest fire, generally from needle size up to 4" diameter stem), and for NE mixed hardwoods about 12 tons gross per acre of available fuel (62). An average fuel loading of 11 tons per acre can be estimated for this region.

The region is at present working on a project correlating the Eastern Region timber types with the NFDR fuel models, along with quantified fuel loading by type and other factors. Hopefully, their project and "Guide for Fuel Type Identification" should be completed by the end of 1973.

4.5.9 Region 10, Alaska Region - (63)

Alaska, the largest state in the United States, has a total land area of 365.5 million acres (16% of the total are in the United States) and extensive forest areas (16% of the forest land in the United States or 119 million acres). For forest inventory purpose, the state is divided into two regions, Coastal and Interior.

The Coastal forest comprise 13,247,000 acres and is an extension of the rain belt forests of Oregon, Washington, and California. An important difference is that the Douglas-fir is not found in Alaska. Western hemlock and Sitka spruce forest types together account for 96% of the Coastal forest area. Western hemlock is dominant on about 2.7 million acres and Sitka spruce on a million acres. On another 1.5 million acres, hemlock and spruce are mixed, with spruce making up 30 to 49% of the stand. Some cedar, western redcedar and Alaska-cedar, and hardwoods such as black cottonwood and birch are also found. In the transition area from coastal to interior forest types, the western hemlock-Sitka spruce type is displaced by white spruce and mountain hemlock in mixture with aspen and paper birch. The average volume per acre of saw timber stands in Coastal Alaska compares favorably with similar stands in Oregon and Washington. The Coastal forests are well protected from fire by the heavy rainfall which is well distributed throughout the seasons.

Alaska's Interior forested area is about 106 million acres. The interior forest types are mixtures of four major commercial species: white spruce, paper birch, aspen, and balsam poplar. The Interior stands are similar to some in the Lake States (Minnesota, Michigan, and Wisconsin), and compare favorably with such stands in volume and quality. Fire consumes an average of more than a million acres each year of the Interior forests. Accurate information concerning the total area burned, the types of vegetation destroyed, the amount of timber killed, and other damage appraisal information is difficult to obtain because of the remoteness of the region and the difficulty required to fight the fire. The weather changes usually extinguish these remote, inaccessible fires.

For fuel loadings, the estimates utilized for the Pacific Northwest Region can be projected for the Coastal area (60 tons/acre) and the estimates for the Lake States projected for the Interior forest area (11 tons/acre). Taking into account the acreage of each forest area, the average fuel loading for Alaska is 16 tons/acre.

4.5.10 Summary of Regional Fuel Loadings

It is very difficult to assess a so-called average fuel loading or average fuel consumption by wildfire for a large geographic area. This is especially true when there is a diverse and heterogeneous vegetation cover. Conversely, if a relatively homogeneous fuel cover type exists, a fairly accurate fuel assessment can be projected.

A subdivision of geographic areas into regional units reduces the bias of the extremes of the averge loadings to a lower order of magnitude. Eventually, as the geographic units or blocks become smaller, the reliability or accuracy of the estimated fuel loadings and/or fuel consumption would be more closely related to the actual field condition and may even reflect seasonal variations.

In this report, estimates were made for the U.S. Forest Service's geographic areas and regional units. The use of an estimated fuel loading is recognized as a first step in obtaining values relating actual fuel load conditions to a geographic unit.

Table 10 is a summary of the estimated fuel consumed by wildfire for the geographic areas of states and the regions within the area. The estimate of the quantity of fuel consumed by a fire (or estimate of fuel remaining) varies with the intensity (flaming combustion) and duration (glowing combustion) of the wildfire.

Table 10

SUMMARY OF ESTIMATED FUEL CONSUMED BY FOREST FIRES

Area and Region	Average Fuel Loading (estimated) tons/acre
A. Rocky Mountain Area	37
Northern, Region 1	60
Rocky Mountain, Region 2	30
Southwestern, Region 3	10
Intermountain, Region 4	8
B. Pacific Area	19
California, Region 5	18
Pacific Northwest, Region 6	60
Alaska, Region 10	16
coastal	60
interior	11
C. Southern Area	9
Southern, Region 8	
wildfire	9
prescribed fire	3
D. Eastern Area	11
E. North Central Area	11
Eastern, Region 9	
conifers	10
hardwoods	12

5. EMISSIONS AND EMISSION FACTORS

The information search has revealed a lack of pertinent experimental data on the emissions from wildfires. Data and measurements reported in the literature have been obtained on laboratory fires, burning towers and from prescribed burns. Although scaling of such data to wildfires is frowned on by experienced forest fire personnel, all collected data and measurements were assessed and categorized into original and quoted data.

The experimental data obtained from non-wildfires have limitations of not being realistic. In a non-wildfire, the fuel history, fuel, fuel arrangement, and environment is a simulated, controlled area of combustion. The forest is artificial although the emissions that are generated are real and tested with standardized and recognized sampling methods for the fuel under study. These small scale studies were an extension of past experiments on the pyrolysis or combustion of wood and could be utilized to study the emissions of the various components that make up the forest fuel. The emissions from the burning of selected components of forest fuels under varying simulated field conditions would provide an insight to the total forest fire picture. Such emission measurements, although of an arbitrary source, have an essential experimental value.

On the legal side, control of a wildfire situation is under the jurisdiction of governmental agencies with a commitment to suppress and extinguish a wildfire. The interaction of an adequate field study of forest fire emissions with present day available technology would probably interfere with the operation of fire control personnel.

However, in the future, the emissions from a real wildfire would require testing in order to verify the laboratory studies. This will be a case of a real fuel situation with an arbitrary testing method. The fuel consumed and quantity of emissions produced under the prevailing measured environmental and meteorological conditions would need to be determined. The sampling of the emissions would be difficult to do in a real forest fire situation without the assistance of Forest Service personnel.

5.1 Wood Chemistry

Although the burning of wood is a complex process, the development of emission factors requires a more general outlook of the process as a first approximation. A detailed analysis of the various reaction mechanisms, burning stages, or the composition of the wood, bark, and leaves that go into the total combustion process could not be found in the information search.

Wood as a forest fuel is in various stages of development from living, growing vegetation; dormant, live vegetation; dead and dry vegetation; and finally the natural decomposing vegetative matter. Thus, combustion of forest fuel is complex or simple depending on the outlook and degree of quantification that is sought. An analogous description would be the perspective to an amoeba in biology. From one viewpoint, it is a *simple* single-celled organism; but from another viewpoint, it is a *complex* animal in that all body functions involve a single cell with no obvious differentiation.

5.1.1 Chemical Composition

The following is a general description of the chemistry of wood. A description in much greater detail may be obtained from references and textbooks (64,65).

Wood is a complex material of chemically different components called cellulose, hemicellulose, lignin and a group called extractables (oils, pigments, minerals, and other organic substances). The cellulose, hemicellulose, and lignin constitute up to 90-95% of the weight of oven-dry wood. The woods of various species consist of the same main components but in different proportions; the largest difference exists between the two main groups, conifers and deciduous trees. Conifers have a higher proportion of lignin (28-34%) while deciduous trees average less (18-27%). The extractables or the extraneous components (5-10% are the constituents that vary greatly between species, between trees in the same species, and even within parts in the same tree. The organic fraction of the extractables consist of many classes of compounds; aliphatic and aromatic hydrocarbons, alcohols, aldehydes, gums, sugars, etc.

Although the number of organic compounds is large, 90-95% of the dry weight of wood is composed of the three components with cellulose predominating, and thus there is a chemical limitation in its usage as a fuel that would minimize the kinds and quantities of emissions during the pyrolytic decomposition and combustion of wood. The bulk of the emissions generated will be from the three components.

The moisture content of green wood (freshly cut) varies from 30 to 60 percent. Air drying for approximately one year reduces the moisture content to 18-25%. Wet bark may contain 80% or more moisture while the air dried bark approximates 5-10%. Thus, in burning green twigs and branches, approximately 50 to 60% of the moisture is evaporated and released into the atmosphere. The dry litter containing 5 to 20% moisture requires less of a heat flux to attain the temperature where exothermic reaction takes place.

5.2 Pyrolysis and Combustion

In a forest fire, the dry combustible material is consumed first, and if the energy release is large and of long enough duration, drying of green, live material takes place with subsequent burning of this material as well as the larger, dry material. Under proper conditions, this process may develop into a chain reaction with a resultant forest fire, With optimum environmental and fuel conditions, a conflagration may result.

The pyrolysis and combustion of wood have been extensively studied for many years. Both are complex reactions and are continuously studied by fuel chemists. However, for this program, only a general description of the process of pyrolysis-combustion of the forest fuels will be used to provide background to the development of emission factors.

In pyrolysis, heating is done in the absence of oxygen with resultant charcoal, organic tars, and gaseous emission products. Variations exist in the pyrolysis products of different trees and tree components but the greatest variation exists between hardwoods and conifers.

In combustion, heating is done in the presence of oxygen and with complete combustion, the hot volatile combustible gases are in contact with sufficient oxygen producing carbon dioxide, water vapor, and inorganic ash.

There are several properties of wood that relate to combustion and its attendant emissions. Dry wood is very hygroscopic and the amount of moisture adsorbed depends mainly on the relative humidity and temperature. The exceptions are species having high extractives content, such as cedars and redwoods. In green wood, the cell walls are saturated with moisture, while the cell cavities may be incompletely or completely full of water. The moisture in the cell walls are called "bound" water, while moisture in the cell cavities is called "free" water. "Free" water removal has little or no effect on many of the properties of the wood, while the removal of "bound" water affects its properties.

5.2.1 Pyrolysis

Decomposition of wood by heating in the absence of air is an ancient process. The decomposition and the amount of resultant products depend mainly on the heating temperature, duration of heating, the surrounding medium, and the wood species. When wood is exposed to a heat flux, the wood heats up by conduction and when the surface layer becomes hot enough, water vapor starts to evolve. As heating progresses, the surface layer starts to char and other gaseous volatiles evolve. On large pieces of wood, as the interior becomes hotter, the pyrolysis effects go deeper, but the outward flow of volatiles convect heat back to the surface. Thus, on very large pieces of wood, charring effects are observed on the surface, which acts as a thermal insulating barrier.

The hemicelluloses decompose first, then the cellulose, and then the lignin. The extractables evolve on the basis of their volatility and reactivity at the higher temperature. The time-temperature relationship of heating and their products has been extensively studied. The course of pyrolysis can be presented on the basis of zones of heating in relation to the temperature applied. The initial heating results in an endothermic reaction where the gaseous products are largely non-combustible. Further heating results in an exothermic reaction (about 280-300°C) with the liberation of large amounts of carbon dioxide, carbon monoxide, and a liquid distillate containing acetic acid and its homologs, methanol, and light tars. Further high temperature heating results in the production of hydrogen and heavy tars.

The pyrolysis of wood yields carbon (charcoal), an aqueous distillate, an oil distillate, and gases (carbon dioxide, carbon monoxide, various hydrocarbons, and hydrogen). The products of pyrolysis vary considerably and depend on the tree, the conditions of the reaction, the final temperature, and the duration of heating. The extensive laboratory studies (64,65) in the pyrolysis of wood have been extended to include mathematical models of wood pyrolysis (66), and a critique of the present state of knowledge (67).

Broido and Martin (68), in their study on the addition of inorganic solids to enhance the tendency of cellulosic solids to glow and thus minimize the tendency of the flaming reaction to occur, also analyzed the volatile pyrolysis products of treated and untreated alpha-cellulose samples by means of gas chromatography and mass spectrometry at two different irradiance exposures. Volatiles measured were carbon dioxide, carbon monoxide, hydrogen, methane, ethylene, and ethane. The alpha-cellulose samples treated with potassium bicarbonate (flame retardant) produced more of the gases than the untreated samples.

The Northern Forest Fire Laboratory has a broad study in the relative importance of the chemical constituents of wildland fuels. The wildland fuels differing in mineral compositions showed quite dissimilar emission properties (69). The silica fraction was found to be unimportant when relating ash content to pyrolysis and ignition of two highly combustible grasses (70).

In the disposal of logging slash by burning, selection of optimal burning methods must be considered as it relates to cost, fire control, and air pollution potential. A laboratory simulation of wood pyrolysis under field burning conditions was made in which the thermal environment could be controlled and the outputs such as specimen weight loss and particulate production rate could be measured. Thus, various chemical treatments of fuel with chemicals, such as retardants, could be studied as possible reductants to air pollution. On a limited basis, as yet no evidence has been found that flame retardant treatment under otherwise controlled conditions result in the reduction of air pollutants (71).

On the contrary, a study of two flame retardants on particulate and residue production (72) indicated that ammonium sulfate (AS) had little effect on particulate production but diammonium phosphate (DAP) produces substantial increases in particulates on burning. The range of particulates produced per unit weight consumed was 8 to 94 lbs/ton for DAP, 2.8 to 7.2 lbs/ton for AS, and about 5.5 lbs/ton for the controls where no retardant was used. The fuel was a mixture of Douglas-fir lumber and ponderosa pine sticks at an equivalent loading of 227 tons/acre (slash pile).

5.2.2 Combustion

Combustion is the thermal degradation of the material in air. The volatile vapors escape from the surface and mix with oxygen yielding a flame if conditions are right. A low energy fire (270°C or less) undergoes intermolecular dehydration resulting in a phenomenon called glowing combustion whereby char and water vapor is produced. In the presence of oxygen, the char sustains glowing combustion with the final products of carbon dioxide and more water vapor. A high energy fire (340°C or higher) undergoes depolymerization resulting in the phenomenon called flaming combustion whereby carbon monoxide and hydrogen is produced. In the presence of oxygen and an ignition source, a highly exothermic gas-phase reaction takes place with extensive flaming. In an intense turbulent wildfire, pockets of combustible gases develop which can flame violently at heights of several magnitudes above the combustion zone.

The complete combustion of a forest fuel will require a heat flux (temperature gradient), adequate oxygen content (air supply), and a long enough duration of time. The distribution of forest fuels vertically and laterally, meteorological conditions, and topographic features interact to modify and change the burning behavior, and thus the fire will attain different degrees of combustion over the period of the lifetime of the wildfire.

Pyrolysis and combustion go hand in hand, and the burning conditions will dictate the proportion of the types of emissions released into the atmosphere. Glowing combustion, backfires, and intense, dry fires have a tendency to produce carbon dioxide and water vapor with less particulates, carbon monoxide, and hydrocarbons.

The U.S. Forest Service has a publication describing forest fuels, prescribed fire and air quality. The information on the physical and chemical properties of smoke resulting from combustion of forest fuels, primarily wood, is presented to indicate the complex nature of the emissions that can be produced (73).

5.3 Measured Emissions

The information search revealed that research in the emissions produced from forest fuels developed within the past 15 years. The early investigations covered the area of burning in an incinerator. As concern for air quality developed, studies were directed on open field burning of grasses and stubble, agricultural burning of orchard trimmings and landscape materials and the burning of forest fuels.

General articles reviewing the quantities of the emissions produced by forest fuels were available in references to a single pollutant or to the recognized pollutants as defined in the Clean Air Act of 1970. These emission values were summarized in the EPA publications (1,74) and were first approximations, rough estimates, or small-scale laboratory studies. Efforts to locate real wildfire data were not successful.

The following data in Table 11 is a compilation of the information gathered on emissions that were published on forest fuels or related fuels. All data were referenced on the basis of actual experimental data, except for the EPA nationwide values which are composite values of the best available data and information at that time.

Review articles as well as approximations of emissions produced by forest fuels were available. Some of the more

Table 11
PUBLISHED EMISSIONS/EMISSION FACTORS (#, #/ACRE, #/TON)

No.	Geographic Area	Fuel Type - Quantity	Emission of Interest									Ref.
			Particulates		Hydrocarbons			CO	SO_x	NO_x or N_2	CO_2	
			Filterable	Total	Reactive	Non-Reactive	Total					
1	Nationwide	Uncontrolled Fires 4.57 million acres (145.6 million tons)		6.7 million tons/year			2.2 million tons/yr	7.2 million tons/yr	Neg.	1.2 million tons/yr(NO_x)		AP-73, 1971 (74)
		Controlled Fires 3.52 million acres (76.4 million tons)										
2	Nationwide	Open Burning										
		-As Agric. Field		17 #/ton			20 #/ton	100 #/ton	Neg.	2 #/ton(NO_x)		AP-42 (revised) 1972 (1)
		-As Landscape		17 #/ton			20 #/ton	60 #/ton	Neg.	2 #/ton(NO_x)		
		-As Wood		17 #/ton			4 #/ton	50 #/ton	Neg.	2 #/ton(NO_x)		
3	California	S.F. Bay Area		24 #/ton	30 #/ton	166 #/ton		600 #/ton	-	-		Feldstein et al, 1963 (75)
4	California	Bay Area			(As Unsat.)	(As Sat.)						Darley, et al, 1966 (76)
		Fruit Prunings, 11% MC			2.1 #/ton	0.5 #/ton	4.2 #/ton as C	46 #/ton			2258 #/ton	
		Fruit Prunings, 35% MC			6.8 #/ton	1.3 #/ton	9.7 #/ton as C	66 #/ton			1995 #/ton	
		Native Brush, 5% MC			3.0 #/ton	0.5 #/ton	4.7 #/ton as C	65 #/ton			2620 #/ton	
		Native Brush, 13% MC			2.4 #/ton	0.6 #/ton	4.4 #/ton as C	55 #/ton			2394 #/ton	
		Fir Chips, 5% MC			0.5 #/ton	0.1 #/ton	2.8 #/ton as C	35 #/ton			1526 #/ton	
		Redwood			0.5 #/ton	0.1 #/ton	2.2 #/ton as C	70 #/ton			3742 #/ton	
		San Joaquin Valley			(As Unsat.)	(As Sat.)						
		Native Brush, Dry			1.9 #/ton	0.5 #/ton	4.7 #/ton as C	70 #/ton			2733 #/ton	
		Native Brush, Dry&Green			8.7 #/ton	1.1 #/ton	15.2 #/ton as C	81 #/ton			1990 #/ton	
		Native Brush, Green			14.2 #/ton	2.1 #/ton	27.4 #/ton as C	134 #/ton			1528 #/ton	
5	California	Agricultural and Forest Fuels, Dry					4-18 #/ton Ave. 14 #/ton	40-140 #/ton Ave.92 #/ton		50 PPM(NO_x) at Temp.Peak	1600 to 2500 #/ton	Darley, et al, 1972 (77)
		Green Fuels & Wet Dead Fuels					Increases	Increases			Decreases	
		Grass		16 #/ton								
		Woody Materials		11-17 #/ton								
6	Oregon	Williamette Valley					(as C)					Boubel, etal, 1969 (78)
		Lab-Straw & Stubble Residue, Grass		10-17#/ton Ave. 15.6 #/ton	4.48 #/ton (Total Olefins)	1.74 #/ton (as Sat.)	4-19 #/ton Ave. 12.3 #/ton	56-147 #/ton Ave. 101 #/ton		29.3 PPM as(NO_x)		
		Field Studies		Ave. 15.55 #/ton			Ave.10.55 #/ton	Ave. 132.2 #/ton				
7	Washington	Slash-Broadcast Fire										Fritschen et al, 1970 (79)
		Ground-Stage I		1,150 $\mu g/m^3$			-	6.5 PPM			555 PPM	
		Ground-Stage II		1,510 $\mu g/m^3$			6 PPM	13.8 PPM			625 PPM	
		Ground-Stage III		950 $\mu g/m^3$			2 PPM	6.6 PPM			543 PPM	
		Aircraft-Stage II		960 $\mu g/m^3$			2 PPM	0			330 PPM	
		Lab-Hemlock		2.0 gm/kg			1.2 gm/kg	38 gm/kg			1121 gm/kg	
		Lab-Douglas Fir		2.3 gm/kg			1.6 gm/kg	32 gm/kg			1143 gm/kg	
		Lab-Red Cedar		2.0 gm/kg			2.2 gm/kg (as C)	57 gm/kg			1474 gm/kg	
8		Landscape Refuse (lawn clippings, leaves, and tree branches)		17 #/ton		30 #/ton (as methane)	65 #/ton			4 #/ton(NO_x)	700 #/ton	Gerstle, et al, 1967 (80)
9	North Carolina	Loblolly Pine Litter, Green Needles								10 #/ton(N_2) 24 #/ton(N_2)		DeBell, et al, 1970 (81)
10	South Carolina	Coastal Plain Forest Floor								20 #/ton(N_2)		Wells, 1971 (82)
11	Montana	Douglas-Fir Lumber Ponderosa Pine Sticks		5.5 #/ton								Philpots, et al, 1972 (72)
		"Average" Forest Fuel (Litter, Understory, Crown)		17 #/ton			18 #/ton	140 #/ton		4 #/ton(NO_x)		

complete reviews with discussion and bibliography were very helpful in the information search (16,73,83,84,85,86,87).

An overall discussion and review on the emissions, concentrations, and fate of gaseous atmospheric pollutants from sources including forest fires were prepared by Robinson and Robbins (88).

The particulates produced by forest fires range in size from the invisible (less than 0.1 µm) to large fire brands. Below 0.1 µm in diameter, the particles are incapable of effectively scattering light, but may be potentially more undesirable due to their long residence time in the atmosphere. Particulates as related to air pollutants are in the size ranges (0.001 - 10 µm) that remain suspended in the air. Thus, sampling procedures must take into account the extremely small particle sizes which contribute greatly to opacity and atmospheric load. The larger particles fall out of the atmosphere in a short period of time. Nuclei from grass have been estimated at 2×10^{22} particles per acre (89). Condensation nuclei and ice nuclei have also been measured from forest fires and cane fires (90,91).

A particle size distribution of the smoke generated from buring wood sawdust and shavings was obtained with the aid of an electron microscope (92). The samples were collected by an electrical charging method onto carbon films and prepared for examination by shadowing with 40-60% gold-palladium at an angle of 20° to the plane of the supporting carbon film. For wood smoke, the geometric mass mean radius was 0.035 µm with a geometric standard deviation of 1.7.

Other studies have been conducted on smoke from forest fuels. In the jarrah (Eucalyptus) forests of Western Australia, low intensity managed fires that are lit by aircraft and cover up to 50,000 acres in a single day are used to reduce the fire hazard. Numerous studies have been conducted on how bushfire smoke affects air quality. A light aircraft was used to collect smoke samples, which were analyzed for particulate matter and gaseous products. The results suggest the bushfire smoke is not involved to any serious extent in the production of photochemical smog over the Australian continent, but that the yield of particulate matter from a fire is large, and the build-up of smoke reduces vision through the atmosphere (93).

For the fuels of Western Australia, the smoke composition averaged: tar 55%, carbonaceous residue 25%, and ash 20%. The total weight of solid particulate matter arising from a typical prescribed fire was 1.5% of the litter quantities on the ground. Most of the particles were less than 1 μm in diameter, with the majority of these approximately 0.1 μm in size. The larger particles (≤ 50 μm) seemed to be agglomerates of a tarry nature. Single tar particles were smooth and spherical and were usually slightly more than 0.1 μm in diameter, but the other "crystalline" particles were smaller than 0.1 μm. The concentration of particles in the thicker smokes appeared to be between 10^5 and 10^6 particles per cm^3 (93).

The natural organic emissions from forest trees have been reported in the literature. These and the other components of the leaves and needles are the most vulnerable in a forest fire. At the present time, the Southern Forest Fire Laboratory in Macon, Georgia, is conducting emission tests on various conifer needles and hardwood leaves. Preliminary results on these fuels, wind tests, and slope tests have been obtained. Further tests are anticipated before the results will be available for use.

5.4 Summary of Emissions

From the information search, the available data on emissions from forest fires were compiled and tabulated. Analysis of the tabulation indicated that the measured emissions did not vary greatly in magnitude except for the values obtained for carbon monoxide. Variability existed in the amount of measured carbon monoxide, since the degree of the pyrolysis-combustion stage, temperature level, residence time, and point of sampling all have a direct relation to the measured value.

Nitrogen oxide production is related to the temperature of the fire and residence time and is not frequently measured in a laboratory fire. A general rule of thumb applicable to particulates from a forest fire would be: the total weight of solid particulate matter emitted to the atmosphere is 1 to 2% of the original fuel quantities found on the ground. No investigator has separated the particulate catch from forest fires into "filterable" and "total" fractions. Thus, no estimate of these fractions can be reported.

The hydrocarbons were not adequately categorized in the literature by the researchers on forest fuels. The data available were for brush and grass residue, and the estimated emissions were 9 lbs per ton of reactive hydrocarbons and 2 lbs per ton of non-reactive hydrocarbons. Until more data are reported in the literature, only total hydrocarbons will be reported here.

Discussion with the researchers indicated that the preliminary experimental results of the Southern Forest Fire Laboratory and the bush fire smoke results obtained in Australia compare quite favorably with Dr. Darley's numerous reported results. The emission values taken from Table 11 for use in determining the emission factors were measured and reported by Dr. Darley and co-workers. Darley's results are from small samples that were test burned at the University of California at Riverside. These burning tower studies were either reported by his group or referenced by others in preparing estimates of forest fire emissions into the atmosphere. Darley's data indicate that the burning of forest fuel results in the following estimated amounts of solid and gaseous emissions: for each ton of forest fuel; one ton of carbon dioxide, 140 lbs of carbon monoxide, 24 lbs of hydrocarbons as methane, 17 lbs of particulates, 4 lbs of nitrogen oxides, and essentially no sulfur oxides are produced.

Knowing the yield of pollutants emitted from the burning of a ton of forest fuels and the amount of fuel consumed by wildfire per acre for the defined geographic area, the emission factors can be calculated. The amount of pollutants emitted by burning forest fuels is relatively constant but the fuel amount can vary considerably with the geographical area. For this report, the fuel quantity selected in determining the emission factor is the amount of fuel consumed under a set of average fire conditions for that area. This is usually called the "available fuel".

The emission factors and the total emissions produced from a forest fire for each geographic region is calculated from the formulas:

1. Emission Factor (lb/acre) = Emission (Yield of Pollutant) (lb/ton) x Fuel Consumed (tons/acre)
2. Total Emissions (tons) = Emission Factor (lb/acre) x Number of Acres Burned (acres) x a Constant (1 ton/2000 lb)

The emission values presented in Table 11 are the highest in the range of values reported by Darley, et al., for each pollutant. The reason for this was that the most test fuels and burning conditions were not typical of field conditions. The field and laboratory studies on grass and stubble fires correlated well because burning conditions were closely simulated. Experienced forest fire personnel indicate that field fires appear "dirtier" than laboratory fires.

The forest fuel situation, especially for a fire over five acres in size, would also be radically different from the laboratory fire/fuel problem since laboratory burning illustrates the diffusion burning phenomena. The fire behavior of a large wildfire is difficult to simulate and is unique and different from a diffuse type of laboratory fire (94). The heat flux, flaming front, convection forces, and the greater mass of green vegetation associated with a wildfire would result in a much higher quantity of pyrolysis products being generated.

Until measurements are made on a wildfire, the present reported data are the best available for the development of emission factors for estimating atmospheric emissions from forest fires.

6. ADJUSTMENT OR CORRECTION FACTORS

After an extensive search of the literature, no reliable analytical data were obtained that could relate emissions to fire behavior parameters. Terrain, density of vegetation coverage, type of vegetation, wind speed, and humidity were related to fire spread, risk, and danger ratings, etc., but not to emission values.

Considerable literature on the parameters that affect the spread of forest fires have been published (95). Three criteria were used to measure rate of spread in forest fires: (a) rate of area growth (acres per hour); (b) rate of perimeter increase (feet per hour); and (c) forward rate of spread of the head or fastest moving portion of the fire (feet per hour). Comprehensive studies have been made on the rate of spread of fires in the field and in the laboratory (18,96,97).

The factors that affect the rate of spread are: (a) weather (wind velocity, temperature, relative humidity); (b) fuels (fuel type, fuel bed array, moisture content, fuel particle size); and (c) topography (solar radiation, slope, profile).

Preliminary studies indicate that fire intensity and direction of fire relative to wind direction does have an influence on emissions, whereas fire spread or rate of spread have an indirect effect on the output of emissions. Fire intensity and rate of spread are not directly related. The U.S. Forest Service studies have been guided and directed for the purposes of learning more about forest fire occurrence, prevention, spread, and control. Recently, studies have been generated on emissions from burning forest fuels as they are related to air quality. The fire behavior and spread studies have indicated the interrelationships among fuel, fuel properties, and environmental conditions in the laboratory and in the field.

Some of these observations are:

1. Rate of spread, flame heights, and fire intensity increase as the amount of fuel increases.
2. Relatively little smoke is produced in burning dry fuel in comparison to fires burning in green vegetation.
3. Changes in wind direction are of major importance in fire behavior
4. Dryness of the atmosphere has significant effect on combustion rates.
5. Steepness of slope, altitude, aspect, position of fire on slope, and the shapes of mountains and canyons are all factors of topography which have an influence on fire behavior.
6. Large forest fires produce great volumes of smoke which vary in character and color in accordance with variations in fuels and rates of combustion.
7. Rate of spread of wildfires has been estimated to approximately double for each 15° increase in slope, if there is no local downslope wind.
8. Head fires are dirtier than back fires (more flaming combustion).
9. Back fires are cooler and cleaner (more glowing combustion).

The recognition of the contribution of forest fuel combustion products to air quality has thus initiated studies to relate the various fire behavior parameters to emissions output. Our extensive reading of the literature indicates that the fuel and fuel particle characteristics are the main factors affecting the quantities and types of emission products produced by wildfires. Topography and wind are indirectly related to the generation of emission products.

6.1 Fuel and Fuel Particle Characteristics

The physical characteristics of fuels and fuel beds influencing fire behavior have been studied intensively (18,98). Besides the fuel type, fuel characteristics of importance are:

1. Distribution of fuel in the fuel bed, by size and condition (live or dead).
2. Fuel loading: fuel weight per unit of fuel bed area.
3. Fuel density: fuel weight per unit of fuel volume.
4. Fuel surface-to-volume ratio.
5. Fuel bed porosity: ratio of fuel bed volume to fuel volume.
6. Moisture content of fuel.

Many of these characteristics will require further field measurements to specify the direct contribution of each factor to the overall average emission value assigned to the geographic area.

At the present time, only a few preliminary data were obtained on emissions as they relate to green vegetation, slope, and wind speed. These preliminary data were obtained in defining laboratory experimental conditions and as such were not released for publication. However, study of the data and related literature indicated that a few conclusions could be inferred for preliminary use. The study shows that the burning of fine green fuels produces approximately three times the amounts of particulates, carbon monoxide, and hydrocarbons than the combustion of a fine dead dry fuel.

7. RELATED STUDIES

During the course of the program, several related areas of study were investigated. These studies were used as a means of obtaining data or a better understanding of the contribution of forest fire emissions to air quality. These study areas were the design of an incinerator, remote sensing, and parametric studies.

7.1 Proposed Design of An Incinerator or Burn Chamber

Data will be needed to correlate fire behavior parameters to actual emissions. The various site visits and literature search showed that the burning towers and the laboratory fire set-ups will require modification for use in determining emissions from various forest fuels and fuel types under differing environmental conditions to reflect an open burning situation. The design must be able to accommodate various fuel and fuel arrangements, as they relate to slope and wind speed. At the present time, it is believed that fuel and fuel properties have a greater influence on the amounts of emissions produced than either wind or terrain

The preliminary design will incorporate the wind tunnel, the environmental conditioning system, moving grate, and a movable flue exhaust hood of the Northern Forest Fire Laboratory, Missoula, Montana, as described in Rothermel and Anderson's paper (96); with the design and usage of the instrumentation at the Statewide Air Pollution Research Center in Riverside, California (76). Modification will be required in all parts of the combined design in relation to dimensions, laminar flow control, and the exhaust portion to obtain open burning conditions in the burn chamber. The structure should be large enough to incorporate the burning of complete shrubs, including chaparral.

One of the many problems to be resolved will be the selection of the proper point or area of sampling, to assure that interreaction in the convection column (chemical reaction and physical agglomeration) is balanced by diffusion and dilution effects. References were made during discussions with forestry personnel to the unstable state of the emission products generated during combustion. Small scale combustion studies show that wood smoke particles vary in kind, number, and size of agglomerates depending on the sampling point. Another area of concern is that the gaseous emission products undergo chemical reaction within the high temperature zone prior to reaching ambient conditions.

The sampling locations must be selected to obtain a representative sample of the emission products entering the atmosphere and still be a physically realistic sample that can be collected or analyzed by present instrumental capabilities. Suggestions have been made to sample at the top of the plume, the top of the convection area, and at the top of the diffuse layer over the fire. Present research studies may clarify or indicate the optimum sampling location in an open combustion process.

7.2 Remote Sensing

Because of the difficulty in obtaining access to a forest fire area, remote sensing of emissions has been the subject of numerous studies and discussions. Ground-based remote sensing, airborne sensing, and even satellite sensing have been referenced in the literature. At the present time, SO_2 and NO_2 surveys have been accomplished by mobile crews on land and in small aircraft by use of sensing devices such as the Barringer Correlation Spectrometer and the newer Cospec II, the Dual-Gas Remote Sensing Correlation Spectrometer, of the Environmental Measurements, Inc. (99).

Airborne sensing has been utilized with instrumented light aircraft -- single engine (100) and twin engine (101) -- to study plumes from slash fires and prescribed burning in this country. Thermal infrared imagery has been utilized by the U.S. Forest Service and others for fire detection, fire location, rate of spread, and direction of spread (102,103). For high altitude atmospheric and meteorological studies, high flying aircraft such as the U-2 have been utilized to obtain samples. At still higher altitudes, satellite pictures from the Gemini-VII have been taken of forest fire plumes (104).

These remote sensing methods are potentially useful to relate forest fire emissions to the fuel source and its characteristics. The use of remote-controlled drones, helicopters, and other ground-related or controlled sampling and detecting devices will require extensive research and development.

7.3 Parametric Study of the Combustion Process

Two conceptual mathematical studies of the parameters that relate to the wildfire combustion process were made. These have been included in this report as Appendices B and C under the names of the respective authors since their efforts were not completely funded by this project.

The study effort was made to illustrate the complex nature of the fuel to fire behavior and, possibly, to the emission output of a forest fire. One approach was based on data to be obtained while the fire was in progress (by the fire control officer) and the other uses data to be obtained after a fire (by the fire survey team). However, due to the shortage of time, the development of both models has been limited to the investigatory and preliminary stages. The results were very preliminary, since no concurrent experimental data were employed. A definite need exists for experimental data, and these models will hopefully be a forerunner of other like studies.

8. RESULTS AND CONCLUSIONS

Table 12 is a complete summary of the emissions and emission factors for wildfires for the various geographic areas and regions. The emission data was obtained from laboratory fires, burning tower experiments, and prescribed burning but not from wildfires.

Fuel loadings (fuel consumed) were obtained from each geographic area or region. The average fuel loading was indicative of the fuel consumed in a wildfire.

The present state-of-the-art shows that no approved experimental data exists on the relation of fire behavior parameters such as type of terrain, density of vegetation coverage, type of vegetation, wind speed, and humidity to the emission factors. Wind and terrain are important complex variables, since local gradient winds differ from regional prevailing winds and their interplay with local diverse topography, especially in the West, makes it difficult to evaluate them with respect to their direct effect on the emissions. Wind provides oxygen but has a cooling effect. Wind provides mixing but conducts radiation ahead of the flame front and thus increases pyrolysis products, especially in a head fire. (As stated previously, a backfire is reputedly a cleaner fire than a head fire.)

Lastly, the information search revealed that wildfire emissions have not been measured. Eventually a wildfire should be sampled for comparison with laboratory data.

Table 12

COMPLETE SUMMARY OF EMISSIONS AND EMISSION FACTORS

Geographic Area	Forest Vegetation of the U.S. (Appendix B)	** Acreage Consumed by Wildfire (acres)	Wildfire Fuel Consumption (tons/acre)	Pollutants							
				Emission Factors				** Emissions			
				Particulate 17 #/Ton* (#/acre)	CO 140 #/Ton* (#/acre)	H-C *** 24 #/Ton* (#/acre)	NO_x 4 #/Ton* (#/acre)	Particulate (tons)	CO (tons)	H-C *** (tons)	NO_x (tons)
1) Rocky Mountain Group	Western Larch-Western White Pine; Ponderosa Pine-Douglas Fir; Lodgepole Pine; Pinyon-Juniper	774,405	37	629	5,180	888	148	243,550	2,005,709	343,835	57,306
Northern, Region 1		351,563	60	1,020	8,400	1,440	240	179,297	1,476,560	253,125	42,187
Rocky Mountain, Region 2		162,795	30	510	4,200	720	120	41,513	341,870	58,606	9,768
Southwestern, Region 3		206,983	10	170	1,400	240	40	17,593	144,887	24,843	4,140
Intermountain, Region 4		53,064	8	136	1,120	192	32	3,608	29,716	5,094	849
2) Pacific Group	Ponderosa Pine-Douglas Fir; Pacific Douglas Fire; Redwood; Ponderosa Pine-Sugar Pine; Pinyon-Juniper-Chaparral	1,161,138	19	323	2,660	456	76	187,524	1,544,314	264,739	44,123
California, Region 5		46,941	18	306	2,520	432	72	7,182	59,144	10,139	1,690
Alaska, Region 10		1,046,542	16	272	2,240	384	64	142,330	1,172,127	200,936	33,489
Pacific N.W., Region 6		67,655	60	1,020	8,400	1,440	240	34,504	284,147	48,712	8,118
3) Southern Group	Oak-Hickory; Oak-Pine; Longleaf-Loblolly-Slash Pine; Cypress-Tupelo-Sweetgum; Chestnut-Chestnut Oak-Yellow Poplar; Mangrove	1,992,339	9	153	1,260	216	36	152,414	1,255,179	215,173	35,862
Southern, Region 8 (Group and Region are the same)		1,992,339	9	153	1,260	216	36	152,414	1,255,179	215,173	35,862
4) North Central Group	Spruce-Fir; Jack, Red, and White Pine; Birch-Beech-Maple-Hemlock; Oak-Hickory; Chestnut-Chestnut Oak-Yellow Poplar	232,749	11	187	1,540	264	44	21,762	179,217	30,723	5,120
Eastern, Region 9 (Both Groups are in Region 9)		349,000	11	187	1,540	264	44	32,632	268,730	46,068	7,678
5) Eastern Group (with Region 9)	Chestnut-Chestnut Oak-Yellow Poplar; Birch-Beech-Maple-Hemlock; Spruce-Fir	116,251	11	187	1,540	264	44	10,870	89,513	15,345	2,558
6) Total United States		4,276,882	17	289	2,380	408	68	618,009	5,089,490	872,484	145,414

* Pollutant Yield, lb pollutant/ton fuel consumed

** Acreage Consumed by Wildfire and Emissions are for 1971.

*** Hydrocarbon as methane

9. RECOMMENDATIONS FOR FUTURE WORK

This section has been divided in two parts: recommendations to the Office of Air Quality Planning and Standards; and an overall recommendation to the EPA.

9.1 Office of Air Quality Planning and Standards R&D

9.1.1 Smaller Inventory Units

The present study showed that data is presently being developed on fuel loadings for various forested areas by the U.S. Forest Service and the U.S. National Park Service. Also, the EPA, various state air pollution control agencies, and forestry commissions have developed rules and regulations for the reporting of open burning, managed burning, and prescribed burning either by a permit system or by an oral or written consent to burn. It appears feasible that an intensive search and retrieval of pertinent information relative to forest fuel burning may extend the development of emission factors and inventories to smaller political boundaries than those of a regional size. A study of this nature would have the following potential benefits:

a.) Knowledge of a smaller unit's contribution to emissions will tend to minimize the extremes in variations found in large areas of diverse forest types.

b.) The areas for which data is either unavailable, inadequate, or incomplete can be pinpointed for further studies.

9.1.2 System of Map Overlays

To facilitate recognition and location of various inventory units, a system of transparent colored maps of fuel, fuel loadings, and the geographic area of interest (state size) would be prepared for use in pinpointing sources or areas of high hazard, risk, and pollution potential.

9.1.3 Inventory Needs and Fire Report Forms

Since the field surveys of fuel, timber, fire control and damage are the responsibility of the U.S. Forest Service, a cooperative, planned effort should be initiated so that data on the whole forest fire process from location, fuel type, fuel consumption, as well as to the emission description, would be reported. This will develop a forest fire report that will give data useful to the EPA and the Forest Service.

9.1.4 Field Study

An area for future consideration is a field study of a real wildfire. The logistics of such a study will be tremendous and will require planning and cooperation. For such a study, suppression and extinguishment should be a parallel effort. There are certain forested locations, usually inaccessible, that may be allowed to burn freely. Another possibility would be to sample in shrub country where periodic burns do occur. In a field study, the top of the convection column, whether as a plume or a diffuse layer over the fire, should be considered the sampling site. Some experts contend that sampling near the combustion zone, in the smoldering area, or too far downstream, yields results that are very different from the emission products and quantities that actually are entering the atmosphere. To prepare for a real wildfire, pilot studies should be designed and formulated to minimize chances of failure.

9.2 General Recommendations

9.2.1 Wood Smoke Composition

Studies have been conducted on bushfire smoke in Western Australia. An intensive study of wood smoke, identification of various forest fuel components, chemical composition, and reactivity in the ambient air (nucleating, scavenging, etc.) would be studied. Particle size measurements as it relates to distance and temperature from the source would be determined.

The scanning electron microscope and the automatic scanning ability of the image analyzer would be utilized. The role of combustion products, specifically particulates from forest fires in the ecosystem, need to be studied.

9.2.2 Modeling Studies of Emissions from Fires

Two conceptual models have been initiated and presented in this report. At this time, there is a noticeable lack of experimental data that could be utilized in modeling. The usual approach to modeling has been to compile experimental data for use in preparing a model. Since there was no wildfire emission data nor any qualified laboratory emission data relative to fire behavior parameters, a recommendation is made to prepare an experimental study such that the minimum inputs necessary for a model is designated and then obtained so that only the essential number of experiments and data are taken. This will optimize the research effort in studying the parameters that relate to the wildfire combustion process.

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Appendix A

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Appendix B

MATHEMATICAL DESCRIPTION OF FOREST FIRE EMISSIONS

by Dave Becker

MATHEMATICAL DESCRIPTION OF FOREST FIRE EMISSIONS

1. INTRODUCTION

When a forest burns, a large diversity of materials are consumed: various species of trees, goundcover, duff, etc. By estimating the amount of each of the materials consumed and its average chemical composition, the total amount of each freed element can be estimated, especially total carbon. The question is then, in what ratios do the various possible combustion products occur: carbon monoxide, carbon dioxide, saturated hydrocarbons, etc? This question is extemely difficult and its complete solution would require a detailed specification of the physical and chemical states of the fuel, the meteorological conditions and the detailed history of each burn. This task would be monumental. The state of the fuel alone involves the variation of the composition of the forest with species, geography, season, climate and other factors. Moreover, the many chemicals released during the burning process can interact in many ways to produce many products via many alternate pathways. Additionally, the description of the burning process itself in terms of physical parameters is a detailed and not altogether solved problem - even in principle. With these considerations in mind, IITRI seeks to establish a model of the emission process, which, though crude, would relate some of the average chemical and physical properties of the evolved emissions to the available parameters.

In constructing such a model for practical application, it is essential that the simplifying assumptions yield a set of equations that only rely on directly obtainable measurements and, perhaps, a small number of free parameters. Alternatively, the model can contain parameterized experimental data, unsupported by basic theory -- a more pragmatic approach. Whenever possible, the model should incorporate the measurements and indices already being taken and calculated, respectivley, by the Forest Service. Fortunately, the U.S. Forest Service has been studying forest fires for a long time, and has accumulated data in standardized format on several aspects of the fires that are relevant to silvicultural and safety concerns. Several investigators have studied this data and have established quantified relations among the various fire aspects (rate of speed, wind velocity, fuel loading, etc.)* However, these relations contain only half of the necessary information. They describe the physical conditions under which the chemical reactions occur. To formulate an emissions model, the chemical reactions must be quantified in terms of the physical conditions. There are many ways in which this can be done, depending mainly on what aspects of the emission the model is expected to predict, and with what accuracy. In this report, the basis for several different kinds of models -- based on several different degrees of chemical characterization of the emission -- are discussed. It is concluded that owing to a scarcity of emission data, a desire to frame equations that will be solvable in the field, and the incomplete current understanding of many of the underlying processes; the initial effort should be concentrated on the most pragmatic approach. Later, when the understanding is more complete, it will become appropriate to study the more detailed models and to present the results as a reference table, rather than equations.

The following section will describe some mathematical relations that have been derived from the available fire models. These relations will be used to parameterize the emission conditions and the chemical reactions. Following that section, additional sections will discuss, in detail, several different chemical models.

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* Some of the relations are founded in models; others are only "curve fits".

2. FIRE - PROCESSES AND PHYSICAL PARAMETERS

2.1 Time Dependent Behavior of the Emissions

Before beginning the mathematical treatment, consider the time history of a given fuel element that is consumed in the fire. As the fire approaches it, its temperature gradually rises from that of the ambient atmosphere to that required for thermal decomposition. At the thermal decomposition threshold, the fuel element gradually begins to evolve gas. The distribution of chemicals within that gas can be well predicted from pyrolysis data at that temperature, as there is no excess of atmospheric oxygen within the fuel element. At that preignition temperature, the gas is not further oxidized and the pyrolytic chemical distribution is the same as the emission chemical distribution to the atmosphere. As the fuel element and its surroundings reach the ignition temperature, the chemical composition of the emitted gases is changed from the pyrolytic distribution by oxidation in the flame. Moreover, on leaving the flame, the reaction products are subject to coalescence and agglomeration. These processes are primarily restricted to the time period during which the products remain within the plume. There, inter-emission particle collisions are most probable. On emerging from the plume, the gases and particulates disperse throughout the atmosphere as before. Figure B-1 is a flow diagram that depicts the processes described above.

The major point to be recognized is that the emission characteristics of a forest fire vary with the time history of the burning of each fuel element. Moreover, the burn history varies greatly from fire to fire and is difficult to predict because it is dependent upon some factors (especially the geometry of the fuel arrangement) that are difficult to measure with sufficient accuracy, in practice. Thus it is proposed that the time history of the burn be treated as an observable itself.

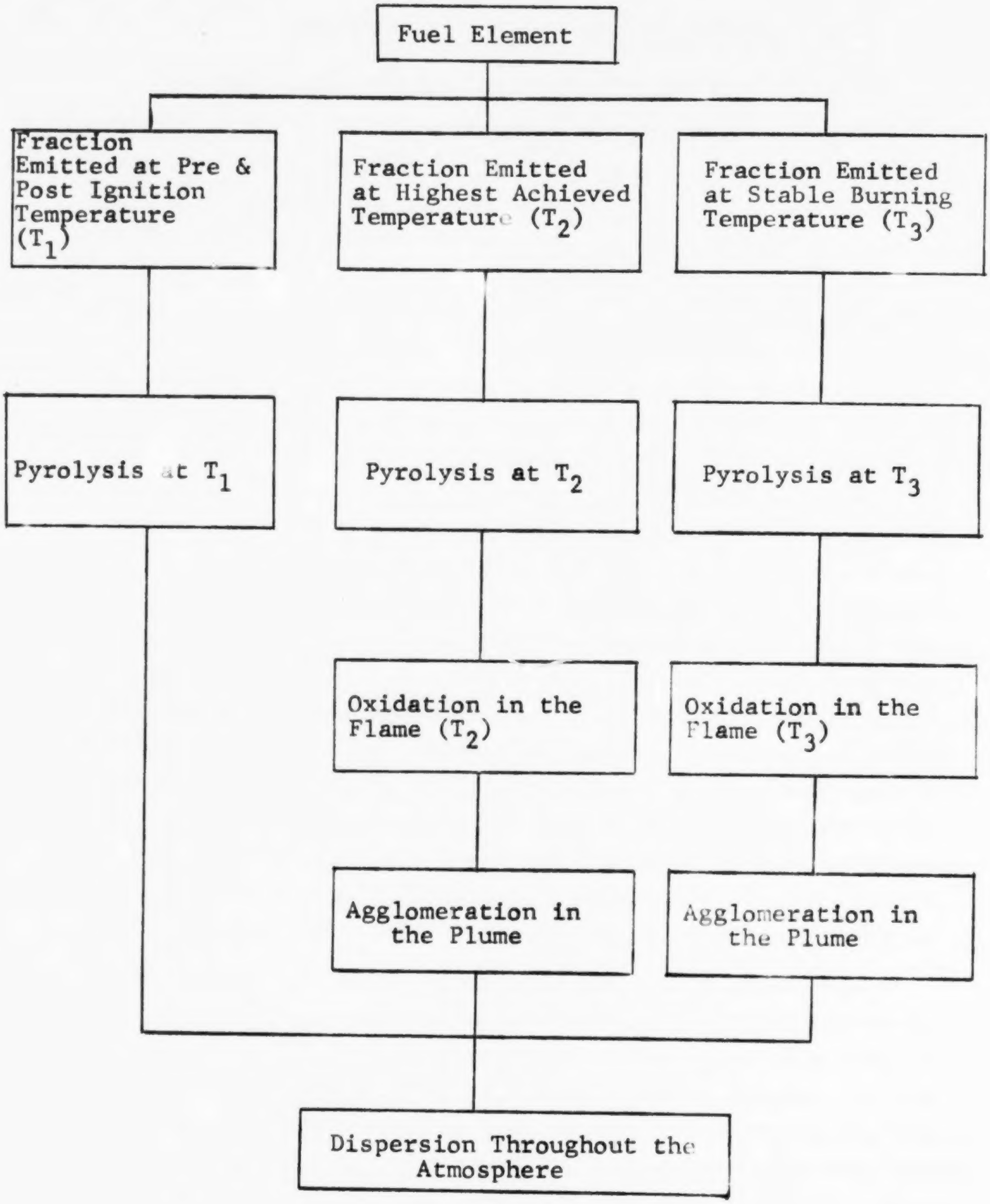
Fuel Element
Fraction Emitted at Pre & Post Ignition Temperature (T_1)
Fraction Emitted at Highest Achieved Temperature (T_2)
Fraction Emitted at Stable Burning Temperature (T_3)
Pyrolysis at T_1
Pyrolysis at T_2
Pyrolysis at T_3
Oxidation in the Flame (T_2)
Oxidation in the Flame (T_3)
Agglomeration in the Plume
Agglomeration in the Plume
Dispersion Throughout the Atmosphere

Figure B-1

COMBUSTION CALCULATION STAGES FOR A SINGLE FUEL ELEMENT

Figure B-2 depicts the time histories of the burning of three hypothetical fuel elements (a,b,c,). In some cases, such as b, conditions (such as high fuel water content) preclude open flames. In such cases, the fire may smolder for many hours, or even days, until the fuel loading is dissipated. In other cases, such as a or c, a well defined period of maximum temperatures is present and is characterized by large flames. In these cases, though the maximal temperatures are present only for relatively brief periods, much of the fuel is consumed during those periods, owing to the increased fuel consumption rate with increased temperature. However, since higher temperatures are conducive to higher oxidation efficiency, a relatively greater fraction of carbon dioxide and water are produced. In comparing the amounts of emissions produced during the pre-ignition, the full-ignition and the post-ignition periods, it is clear that, in general, none of the periods can be ignored. The emission characteristics of the three periods are roughly compared in Table B-1.

Table B-1

RELATIVE EMISSION CHARACTERISTICS OF THE THREE PERIODS OF THE BURNING OF A FUEL ELEMENT

	Pre-Ignition	Full-Ignition	Post-Ignition
Rate of Fuel Consumption	Low	High	Low to Medium
Time Duration	Short to Long	Short	Medium to Long
Combustion Efficiency	Low	Medium to High	Low to Medium
Resultant Emissions	Low to High	Low to High	Low to High

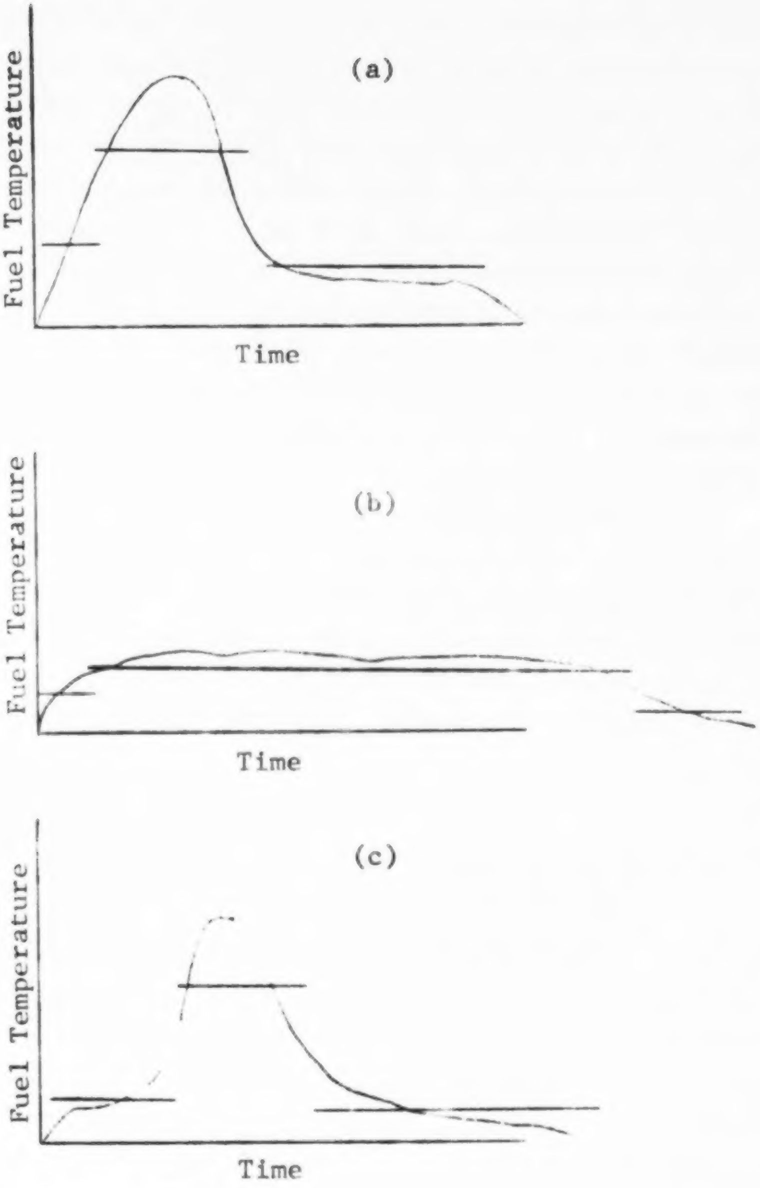

Figure B-2

FUEL TEMPERATURE - TIME

To quantify the emission dependence on burn history for each fire, records should be kept of the time duration of the fire within the three above named burn periods; pre-ignition, full-ignition and post ignition. The horizontal bars in Figure B-2 indicate how these durations would be defined in actual cases. Though this approximation is crude, it is consistent with the accuracy to be expected from field data, and, on that basis, it does not compromise the validity of the model.

In succeeding sections, methodology will be described for the calculation of emissions from the fire. These sections will treat a fire as a constant temperature event. That is, the flame will be treated as being of spatially and temporally uniform temperature, within its boundary. It is to be understood that the uniformity is to apply to each of the three burn periods independently, and that total emissions are always found by summing the emission contributions of all three periods. The temperatures of the three periods will always be denoted herein as T_1, T_2, T_3 in the order of pre-, full-, and post-ignition; or as T; in general. The durations of the periods will similarly be t_1, t_2, t_3, respectivley, or t; in general.

2.2 Relative Significance and Parameterization of Various Fuel-Related Factors

The leftmost column of Table B-2, which appears on the following page, details 11 of the most significant factors that determine the chemical composition of the emissions. The second column of the Table lists those (of three) fire behavior parameters to which each factor relates. The third column of that Table contains estimates of the relative significance of each of the factors for each of the fire behavior parameters. A "1" signifies high significance and "2" and "3" signify progressive lesser levels of significance. It is recommended, at least initially, that effort be concentrated on only the most significant factors.

Table 6-2

FACTORS AFFECTING THE CHEMICAL PROPORTIONS OF EMISSIONS

Factor	Fire Behavior	Order of Effect		
Wind	Fire Temperature	1		
	Fuel Mixing	1		
	Fuel Residence Times	1		
Rain/Humidity	Fire Temperature	1		
	Fuel Residence Times	1		
Season of Year	Fire Temperature	1		
	Fuel Residence Times	1		
Time of Day	Fire Temperature		2	
	Fuel Residence Times		2	3
Topography	Fuel Mixing	1	2	
	Fuel Residence Times		2	
Time History of Burn	Fire Temperature	1		
	Fuel Mixing	1		
	Fuel Residence Times	1		
Control Measures Applied	Fire Temperature		2	3
	Fuel Mixing			3
	Fuel Residence Times			3
Fuel Chemical Composition	Fire Temperature		2	3
	Fuel Residence Times		2	3
Fuel Diameter - Ave. and Dist.	Fire Temperature	1		
	Fuel Residence Times	1		
Fuel Density	Fire Temperature	1		
	Fuel Residence Times	1		
Fuel Moisture Content	Fire Temperature	1		
	Fuel Residence Times	1		

The three fire parameters, their definitions, and the motivation for choosing them are:

Fire Temperature - The average temperature in and immediately around the flame, if any; otherwise the hottest fuel temperature. This parameter relates directly to both the chemical and the physical aspects of the problem. Chemically, reaction rates are selectively dependent on it, and physically it is determined by the fuel factors.

Fuel Mixing - The degree to which the vaporized fuel is dispersed with oxygen in the flame. Though it is almost always true that there is more than sufficient oxygen present to completely oxidize the fuel, frequently the fuel forms pockets or streamlines that exclude the oxygen and preclude complete combustion in the flame. Inadequate mixing is a major cause of incomplete combustion.

Fuel Residence Times - There are really two fuel residence times of interest, but one of them relates more to the completeness of oxidation and the other to the size distribution of particulates. The former is the amount of time that a typical fuel vapor element spends within the physical flame. That is, the time between vaporization and emergence from the top of the flame. The other residence time is the amount of time that the fuel vapor element spends within the plume. Note, this definition of Fuel Residence Times is not the same as that of the Forest Service. The two parameters may be related, but not on a one to one basis.

Thus, for example, beginning at the top of the Table, the first factor, "wind", has an effect upon the temperature of the fire, the degree of mixing of the vaporized fuel with the ambient air, and the residence times of the vaporized fuel within the flame and the plume. More specifically, wind affects the fire by several different mechanisms, among which are:

- Wind carries heat away from the flame by mass transport thus lowering Fire Temperature.
- Wind increases the burning rate by increasing the Mixing within the flame and increasing the oxygen supply.
- Wind changes the geometry of the flame and the fuel transport rate which, in turn, changes the residence time and the fractional oxidation.

Similarly, all of the effects of all of the other listed factors can be described in terms of these three basic parameters and the effects which the various factors have on them. Hence, IITRI believes that the physical characteristics of the fire -- insofar as they affect the chemical composition of the emission -- can be adequately described by these three parameters.

2.3 Calculation of the Three Fire Parameters

The calculation of explicit values for the fire parameters for a given fire should be based, as much as possible, on the standard measurements and indices of the Forest Service. This can be readily achieved for the fire temperature parameter. The residence time parameter can be determined via any of several alternate methods. However, they will require some new, but simple, measurements. The mixing parameter is extremely difficult to estimate, but, fortunately, it is believed to be the least variable of the three parameters.

2.3.1 The Fire Temperature Parameter

The fire temperature parameter can be adequantely determined in terms of the indices of the forest service. The average pre-ignition temperature can be estimated by using the ignitability index (1) and by assuming that the fuel is close to the ignition temperature. The full-ignition temperature can be expressed as a polynomial in the Energy Release Component (ERC) (1) of the Burning Index. However, these expressions require that the burning forests be classified according to the Forest Service Fuel Models (1).

2.3.2 Residence Time Parameter

To determine, on the average, how long an element of gaseous fuel remains inside of the flame, two quantities must be determined: the average height of the flame and the average velocity of the gas through the flame. Fortunately, both of these quantities can be expressed in terms of other, more readily measurable quantities, though direct observation of flame height and gas velocity is certainly feasible.

A recent Forest Service Publication (2) gives a derivation for the vertical gas velocity in terms of the plume height. Starting from hydrodynamic equations, ignoring coriolis forces, the vertical geometrical structure of the volume, and smaller corrections, the following relation is derived.

$V = 2.6Z_o^{1/2}$ = vertical gas velocity in meters/second

Z_o = height in meters

Another author gives a semi-empirical expression for the height of the flame (3).

$L = 18.6(R\rho_b'h)^{2/3}$ = flame height in meters

h = depth of the fuel bed in meters

ρ_b' = bulk density of the burned fuel

R = Rate of spread of the fire in meters/second.

Also, the same author gives an empirical expression for the rate of fire spread under wind conditions, namely:

$R\rho_b' = k\ (1 + U)$

where $k = .07\text{kg/m}^3$ for all wildland fires

U = wind velocity

Thus, $L = 18.6\ [k\cdot(1 + U)h]^{2/3} = (18.6)(.07)^{2/3}\cdot$

$[(1 + U)h]^{2/3} = 3.16\ [(1 + U)h]^{2/3}$

and the residence time in the flame is given by:

$$t_F = \frac{1.22\ [(1 + U)h]^{2/3}}{Z_o^{1/2}} \text{ in seconds}$$

Similarly, the residence time of the emission products in the plume is given by the height of the plume divided by the gas velocity

$$t_o = \frac{Z_o}{2.6\ Z_o^{1/2}} = \frac{Z_o^{1/2}}{2.6} = .385Z_o^{1/2} \text{ in seconds}$$

2.3.3 Fuel Mixing Parameter

To date, IITRI has not found a suitable expression for fuel/oxygen mixing, and, one may not yet exist in a form simple enough to be useful (4,5). However, several authors have discussed the problem under the heading "Microdiffusive Combustion", and more work will be required to elucidate the treatments. It is most likely feasible to treat the effect of incomplete mixing as constant, or to parameterize it in terms of flame length and fuel temperature. Either way, it seems that while the effect of mixing is of major importance, its variation from case to case is minimal. One check of this idea can be found in observing smoke plumes. Since the plumes usually have the same general appearance, almost independent of the size of the fire, and since the visual structure of the plume is almost always strongly suggestive of streamline flow, the microscopic flow properties -- including microdiffusion -- are, also, probably nearly independent of the size of the fire.

2.4 Procedure in Calculating the Emissions from a Fire

The following procedure proposes steps to be followed in calculating the emissions from the fire. The point wherein chemical calculations enter the treatment is indicated, but detailed discussion of those calculations does not begin until Section 3.

A. Measure the time duration (t_1, t_2, t_3) of each of the three major periods of the fire (buildup, peak, die out).

B. Characterize the flame temperatures (T_1, T_2, T_3) during each of these three periods via either 1) the U.S. Forest Service Energy Index, 2) the Ignitability Index, 3) direct evaluation, 4) after the fact evaluation -- such as largest diameter trunk burned, rock burned . . . natural scale.

C. Measure or estimate the Fuel Density (ρ), and the depth of the fuel bed (h) and the wind speed U.

D. Measure the height of the plume (Z_o) and estimate the vertical gas velocity via

$$V = 2.6\ Z_o^{1/2}$$

E. Characterize the flame height during each of the three burn periods via either 1) direct observation, 2) formula;

$$\text{Flame height } L = 3.16\ [(1 + U)h]^{2/3}$$

or 3) fire indices.

F. Calculate the residence time in the flame as

$$t_f = \frac{1.22\ [(1 + U)h]^{2/3}}{Z_o^{1/2}} = \frac{L}{V}$$

G. Either estimate the fractional burn of each of the fuel types during each of the periods of the burn or measure the total fractional burn for the entire fire, f_t, and use pyrolysis weight loss rate graphs, as functions of T and t_i to estimate the contribution of each period.

H. Either proceed to I or L for stepwise analysis or overall parameterization, respectively.

I. Use the known T_1, or T_2, T_3 to evaluate the $\bar{\bar{P}}$ (Pyrolysis) matrix -- depending on the particular model chosen.

J. Use the known T_1, T_2, T_3 and t_1, t_2, t_3 to sequentially evaluate the $\bar{\bar{O}}$ matrix depending on the particular chemical model chosen.

K. The fuel mixing coefficient will temporarily be taken to be constant.

L. Solve for the emissions by multiplying.

3. INTERFACING THE PHYSICAL MODEL WITH A CHEMICAL MODEL-OPTIONS

Several kinds of information are required to predict the degree to which oxidation and chemical reaction take place in the flame:

- the concentration of each of the reactants,
- the distribution of the reactants
- the flame temperature, and
- the amount of time during which the reactants are held in proximity of each other.

To specify the data requirements and procedures in greater detail requires that the desired output be specified in corresponding detail. The principal question is "How should the emissions be characterized to yield a model that is both field workable and yet yields useful numbers?" Since there is a consensus among reporting authors that nitrogen oxide formation is negligible (6) except in rare extremely intense fires -- and since the sulfur content of the forest is very small (7) -- the focus turns to the many carbon compounds, and how they should be characterized. Table B-3 details some of the possibilities that were explored, along with some of the associated advantages and disadvantages of each.

The following subsections will discuss each of these options in greater detail. However, before proceeding to those discussions, there is one more consideration that must first be covered -- the mathematical approach to the model. Basically, there are two major types of approaches that may be fruitful for quantifying the emissions: one that traces the stepwise generation/reaction of the chemical species, and another that does not look at the details but instead quantifies the entire process in terms of a complete base set of parameters. To be more explicit, the expression

Table B-3

OPTIONS IN CHARACTERIZATION OF CARBON COMPOUNDS

Option	Advantage/Disadvantage
a. Average molecular wt. of the carbon chains	No structure information, calculation ease
b. Fraction of carbon chains above or below a given molecular wt.	No structure information, calculation ease
c. Distribution of the molecular wt.	No structure information, calculation ease
d. Fraction of the project that has unsaturated bonds; fraction that are saturated	Some structure information, calculation ease
e. Actual distribution of all chemicals present	Most complete structure information, calculation very difficult

would be:

$$E = C \cdot O \cdot P \cdot F$$

where

E represents the emissions

C represents the effects of the plume

O represents the effects of the flame

P represents the effect of pyrolysis

F characterizes the fuel

The variables E, C, O, P and F could be scalars, vectors or n-dimensional matrices depending on the precise formulation of the problem (for instance, the options of Table B-1). However, the order of the factors, in this approach, is always the same. The point is that this approach describes the process sequentially and is based on the equations that describe each process within the sequence. When all the processes are known and are describable, this approach is ideal. When the practical difficulty in using this kind of model becomes large, it is still at least desirable to verify the model by performing some calculations with it. However, it is unlikely that this form of model could yield sufficiently simple equations as to be useful in the field. More likely, it would be solved on a computer to yield easy-to-use reference tables.

The alternate approach is to quantify the entire process in terms of a complete base set of parameters. If we assume, temporarily, that the effect of microdiffusion (fuel mixing) is roughly independent of the particular case, and that breakdown of forest fuel by species is not essential, then the emission process can be adequately characterized by three parameters; the fire temperature and the two residence times. Thus,

$$E = E_i \ (T_f, t_\rho, t_f) \cdot t_i$$

where

E is the mass release rate per unit fuel element for any emission product, and

E_i is a function dependent only on:

t_f = fuel residence time in the flame

t_ρ = emission residence time in the plume

T_f = temperature of the flame

t_i = duration of fire period

Now, however, instead of trying to calculate E by examining the composite processes, proceed directly to emission data and treat the data as a three dimensional (t_f, t_ρ, T_f) curve fit for each chemical emission product that is to be studied. This curve fit can be done by any of several methods: regression analysis, linearization, Taylor Expansion, etc.

If it turns out that it becomes necessary to treat individual forest fuel species separately, then E_i becomes a matrix, but the methodology remains the same. In either case, the resultant description will be sufficiently simple that, in practice, the emissions could be calculated in the field. (Probably simple polynomials in the three parameters.)

Thus, in conclusion, the stepwise calculation approach yields the theoretical functional dependences and allows comparison of each step with auxiliary data, but yields equations that are time consuming to solve. The overall parameterization does not treat the steps independently but does yield simple, consistent equations that summarize the data in terms of the three parameters.

3.1 Complete Chemical Description of the Fire and Emissions

Within this subsection will be discussed all the calculations and procedures that will be necessary to completely model the chemical emissions from the fire. While IITRI does not recommend that this option now be carried to completion, it will be discussed in great detail because all of the other options to be presented are restricted versions of this one. Both approaches (stepwise analysis and overall parameterization) will be discussed, and the former will require more discussion than the latter.

3.1.1 The Overall Parameterization Approach

In this most complete of the IITRI models, the fuel is characterized by specie in a vector*, each position of which indicates the number of pounds of one specie consumed during one of the three time periods ($i = 1, 2, 3$) of the fire, per acre. The calculation of these consumption figures is done in accordance with Procedure G. in Section 2.4. Thus,

---

* Actually an N-Tuple.

$\vec{F}_i = (f_1, f_2, f_j \ldots f_k)$ where k = number of species to be considered

f_j = pounds of specie j consumed per acre during time period i

For each of the k species, a separate regression relation will exist for each of the emission products. Thus, for instance,

$E_{CO_2} = E_{CO_2/elm} (t_f, t_\rho, t_f) \cdot f_{elm}$ = Pounds of CO_2 emitted per acre by the consumption of elm trees during one of the time periods

Thus, the total emission factor for CO_2 per acre for the entire fire is the sum of the matrix products:

$$E_{CO_2} = \sum_{i=1}^{3} \bar{\bar{E}} (t_{fi}, t_{\rho i}, t_{fi}) \cdot \vec{F}_i$$

The determination of the regression relations for the overall parameterization method in this form would thus require measuring, for instance, the CO_2 output of each of the forest species separately over a varied range of conditions. Since this is impractical -- an, most likely, unnecessarily detailed for the needs of the current program -- less exact descriptions of this form will be considered in the following subsections.

3.1.2 The Stepwise Analysis Approach

The stepwise analysis approach follows the flow diagram presented as Figure B-1 in Section 2.1. Beginning with the fuel, the characterization proceeds as in Section 3.1.1. The vector F is calculated, and, as before, it represents the number of pounds of each specie consumed during each of the three time periods (i = 1, 2, 3).

The first step in the combustion process is the volatilization and partial decomposition of the fuel molecules by pyrolysis. The dependence of the chemical composition of the pyrolysis breakdown products on the species of the fuel and the temperature will be retained in this most complete level of description. Similarly, the chemical identity of each of the significant chemicals produced will be retained. Since pyrolysis data has been accumulated for many species of trees at many temperatures (8), there should be little problem in at least approximating its specie and temperature dependence. Thus,

$$\vec{C} = \bar{\bar{P}} \cdot \vec{F}$$

where: $\vec{C} = (C_1, C_2, \ldots C_s \ldots C_N)$ and each C_s is one of the N significant chemicals; P = a K X N matrix each of whose elements describes the temperature dependence of the production of one of the chemicals from one of the K species of fuel.

The next step is the combustion itself, and is the most complex step in the sequence. To discuss this step will require a brief digression into chemical kinetics (9). The rate of a first order, oxidation reaction can be expressed in the form:

$$\frac{d(R_s)}{dt} = -Z_s \cdot \exp\left[-E_{rs}/RT\right] \cdot [O] \cdot [R_s] \text{ for the}$$

reaction $O + R_s \rightarrow O \cdot R_s$ Decomposed and oxidized products.

where:

$[R_s]$, $[O]$ = molar concentrations of oxygen and the s'th reactant, respectively

E_s = activation energy for the s'th reactant going to the r'th product

R = molar gas constant

Z_s = a relatively insensitive variable containing information on the geometry of the reacting volume and the geometry of the reactants. The microdiffusion information should be placed within this variable.

If Z_s and [O] are constant, the equation can readily be solved

$$\frac{d\,[R_s]}{[R_s]} = -Z_s\,[O]\,\exp\left[-E_{rs}/RT\right]\,dt'$$

$$\ln\left[\frac{R_s(t)}{R_s(0)}\right] = -Z_s\,[O]\,\exp\left[-E_{rs}/RT\right]\cdot t$$

Thus, the fraction of R_s that reacts in a short time interval can be readily calculated, provided that the time interval is sufficiently small that only a small fraction of the total population changes and that the oxidation products do not themselves interact, but only oxidize. Under these circumstances, which IITRI believes to hold well for the entire flame, the change in the distribution of chemical products over a short time interval t, can be expressed as:

$$\vec{C}\,(t + \Delta t) = \bar{\bar{O}} \cdot \vec{C}(t)$$

where:

$\vec{C}$ is the chemical distribution vector defined as before

$\bar{\bar{O}}$ is a matrix that describes, in terms of the activation energies and temperature, the decomposition fractions and accumulated decomposition products $\Delta t \lesssim$ the mean reaction time for the shortest lived reactant.

To find the chemical distribution of the emissions that emerge from the flame, the $\bar{\bar{O}}$ matrix must be applied m times, where m is defined by:

$$m = \frac{t_f}{\Delta t}$$

That is, the O matrix must be used a sufficient number of times to fully account for the gases' entire residence time in the flame. Thus, the total chemical emissions ($\vec{C}_T$) can be described by:

$$\vec{E} = \vec{C}_T = [\bar{\bar{O}}]^{m}\left(\frac{t_f}{\Delta t}\right) \cdot \bar{\bar{P}} \cdot \vec{F}$$

The size distribution of the particules would then be calculated by applying the standard particle growth equations* to the emergent chemical distribution, and by assuming that the agglomeration processes are restricted to the residence time of the emission products within the plume, t_p**.

The obvious advantages of this type of treatment of the problem are that it characterizes the emission products in great detail, and that it identifies the processes that are responsible for each of the emission characteristics. However, in view of:

1. the lack of many experiments that determine the factors Z_s, and the virtual impossibility of calculating them;
2. the imprecision in the data ultimately to be collected and evaluated for forest fire air quality impact calculations; and
3. the involved calculational procedures required to use the model, as presented above;

IITRI recommends that, at least initially, the model be simplified to a level more appropriate.

The first approximation to the model that IITRI recommends involves the characterization of the fuel. Since many different species have cellulose and lignin that is virtually identical, and since these are the major components of the wood, it would be advantageous to group the forest growth into a small number of categories, specifically:

- Hardwoods
- Softwoods
- Resinous shrubs
- Non-resinous shrubs

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* See Notes A, B and C.

** See Section 2.3.2.

The water content differences within these breakdowns would be treated explicitly, but the chemical composition would be assumed uniform.

The next approximation involves the activation energies E_{rs}. Since the emissions are almost exclusively carbon compounds, excluding water, and since the bonds that are to be broken are virtually all single or double carbon-carbon bonds, assume that E_{rs} has only two values, one for all single bonds and another for all double bonds. This approximation will not compromise the accuracy of the model significantly.

Next, assume all of the factors Z_s to be constant. This approximation will introduce some error, but since there are only limited suitable data available for analysis, there is little choice. IITRI expects that while this approximation is serious, it will still be consistent with the accuracy of the data.

The final set of approximations involves the characterization of the emissions. For the purposes of the EPA, it may not be necessary to completely specify the chemical composition of the emission. For instance, in terms of air quality it makes relatively little difference whether straight chain saturated hydrocarbons are present as 3, 4, or 5 carbon chains. Even for the organic molecules with ring systems, it is usually more important to know the concentration of ring molecules than to keep a separate record of each type. Several of the possible chemical characterization schemes have already been presented in Table B-3. Now each will be discussed in greater detail.

3.2 Molecular Weight Characterization of Emissions

3.2.1 Stepwise Analysis

One way that the emissions can be characterized is by their molecular weight (MW), or, since they are all composed mostly of carbon and hydrogen, by the number of carbon atoms,

C_x. The emissions can then be conveniently described in terms of a distribution function. Suppose that, within the accuracy of typical forest measurements, the C_x numbers follow a gaussian distribution

$$N(C_\alpha) = N_o \exp \frac{-(C_\alpha - \overline{C}_\alpha)^2}{2\sigma}$$ = fraction of the number of molecules in the emission that have exactly C_α number of carbon atoms

where:

$\overline{C}_\alpha$ = average number of carbon atoms in a chain

σ = parameter descriptive of the width of the distribution

N_o = normalizing factor

Then, using this distributional form, the chemical characterization information is concentrated into three parameters: σ, N_o, and $\overline{C}_\alpha$. To describe how these three parameters evolve in time is thus to describe the distribution.

Fortunately, these parameters have properties that make their calculation straightforward. The initial values of C_α (t=o), N (t=o), and $\overline{C}_\alpha$ (t=o) are calculated from the initial distribution produced by pyrolysis. The calculation then centers on how the flame changes these parameters. There are several ways to proceed at this point, but the following is one of the simplest, and it can be used to describe the others. Temporarily, suppose that all of the carbon-carbon bonds in the emissions have the same bond strength*. Then, except for geometrical factors, the probability of reacting at any one bond is roughly equivalent to the probability of reacting at any other. Moreover, the probability of the reaction occurring at any one site, during the short time interval t, can be explicitly calculated. Using the result of Section 3.1.2,

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* Either picture all bonds as being single bonds or assume that the single and double bonds have roughly equal strength.

$$\ell n\left[\frac{R(\Delta t)}{R(o)}\right] = Z_o \exp(-E/RT) [O] \Delta t$$

setting $\left[\frac{R(\Delta t)}{R(o)}\right] = 1/2$ yields the median time of reaction, for instance:

$$(\Delta t) = \ell n [1/2] \frac{\exp(-E/RT)}{Z_o [O]}$$

where

E = common activation energy for all bonds

Z_o, [O], are defined as in Section 3.1.2

R(t) is taken to represent the number of carbon-carbon bonds.

But, the concentration of oxygen is roughly the same for all fires, so

$$(\Delta t) = \frac{\ell n [1/2] \exp(-E/RT)}{Z'}$$

where

$Z' = Z_o [O]$ and is roughly a constant

When half of the bonds have reacted, on the average, C_α will have been halved. So, in general:

$$\overline{C}_\alpha (t_f) \approx \overline{C}_\alpha (o) \exp\left[-t_f Z' e^{-E/RT}\right]$$

The dependence of σ (t) can also be approximated. σ (o) is known from the initial distribution of pyrolysis products. However, it is also known that if the average number of carbons per chain becomes equal to 1, then σ must equal o. That is, since carbon atoms are discrete, an average of one carbon per molecule means exactly one carbon per molecule. Then,

$$\sigma = \sigma (o) \cdot \frac{\overline{C}_\alpha (t) - 1}{\overline{C}_\alpha (o) - 1}$$

Since the total area under the $N(C_\alpha)$ curve must be conserved, as no carbon atoms are created or destroyed, the dependence of N_o on t_f follows by normalization.

Thus, using this version of the model one can readily predict the average MW, the fraction of emission above or below a given MW, and the total distribution of MWs. Moreover, the concepts herein developed are not limited to gaussian distributions. They can be applied readily to any distribution that is parameterized in terms of mean values.

One interesting variation would be to define either two distribution functions or two groups of chemicals. One function, or group would contain all molecules with at least one unsaturated carbon bond and the other would contain the saturated ones. Then, by following the time evolution of each, the final emissions could be characterized according to the degree to which it is saturated. Naturally, each would evolve differently as the saturated bond activation energy differs by about 20% from that of the unsaturated. This option is especially interesting because the unsaturated bonds are associated with photochemical smog. Thus, a minimal amount of structural characterization could provide sufficient information for some impact analysis.

3.2.2 Overall Parameterization

The approximation ideas of Section 3.1 can also be applied to the overall parameterization method. Thus, since T_f and T_i specify the emissions, along with the fuel characterization -- consider for instance:

$$\overline{C}_\alpha\ (t_f, T) = \vec{S} \cdot \vec{F}$$

where:

$\vec{F}$ is as defined before, except that it now has only 4 elements.

$\vec{S}$ is also a 4 element vector, each element of which depends on t_f and T; and each is fit via an independent regression relation.

Similarly, separate functions could be defined for saturated and unsaturated bonded molecules. These are much more tractable equations than those of Section 3.1.1.

4. CONCLUSIONS AND RECOMMENDATIONS

The mathematical description of the emissions of a burning forest is a complicated problem. However, by making extensive use of Forest Service methodology, restricting questions to the larger aspects of emissions, and neglecting some secondary effects, the problem can be managed.

As a next step in the development, IITRI recommends testing the parametrical relations on actual fire data. The various alternative methods of treatment of the problem vary greatly in the amounts of effort that they require for solution. Also, the predictions of any of these models can be expected to be no better than the data that is fed into them. Thus, before investing effort in a complete version of the model, it is probably best to try the overall parameterization method. followed by a statistical study of those results. Those results can be checked against the general predictions of one of the more detailed models and either verify its essential correctness or indicate where changes will be needed. Moreover, the statistical analysis will also indicate the situations under which additional data will be most urgently needed. Since the amount of data available is small, the analysis should not be lengthy -- but the results will be correspondingly uncertain.

NOTES

A. Decrease of Particulate Number Density with Time (10)

$$\frac{1}{n} - \frac{1}{n_o} = Kt \qquad \text{and} \qquad \frac{dn}{dt'} = -Kn^2$$

where:

n_o = number density at $t' = 0$

n = number density at $t' = t$

K = experimental constant for a given geometry, temperature and pressure

B. Increase of Average Particle Volume with Time (10)

$$\sigma = \sigma_o + Kt$$

where:

σ_o = average particle volume at $t' = 0$

σ = average particle volume at $t' = t$

C. Particle Formation and Growth Rate (10)

$$Z(r) = C(2P)\,\frac{M}{nP}\sqrt{\frac{j}{KT}}\;\exp\left(\frac{-\mu\ \pi\ r^2\ j}{3\ KT}\right)$$

where:

2P = interparticle collision probability

M = interparticle collision probability

P = particle mass density

j = surface tension

K = Boltzman Constant

T = Absolute Temperature

r = particle radius

Z = the number of particles growing to the radius r′, per second

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Appendix C

CONCEPTUAL MODEL OF PYROLYSIS-COMBUSTION OF FOREST FUELS

by Arthur Takata

CONCEPTUAL MODEL OF PYROLYSIS-COMBUSTION OF FOREST FUELS

1. PYROLYSIS AND FIRE CONDITIONS

In this section we are concerned with assessing the state of knowledge in regard to the generation of pyrolysis products both during and following passage of the flame front. Of primary concern here is the determination of the amounts of volatile fuels distilled from wildland fuel during the passage of the front. Following discussions of means for predicting these emissions, the section will culminate with a discussion of the convection columns to which these emissions will be exposed.

To expedite these endeavors, considerable liberties have been taken in simplifying analyses to afford practical predictive schemes. In this regard, semi-empirical approaches were formulated based on the best sources of information -- whether they be experimental or analytical. Only by such techniques, can one achieve the results desired.

2. ESTIMATES OF DEGREE OF PYROLYSIS

In order to accurately predict pollutant emissions,one must first appreciate the quantities of pyrolysis produced which depend on:

- amounts, sizes,and types of fuels
- rate of fire spread
- rates and degree to which fuels are consumed

In the remainder of this section, we shall consider each of the above factors in the order presented.

2.1 Fuel Array Models

Since it is not practical to accurately measure the sizes and quantities of wildland fuels, one must resort to some approximate approach. In view of the similarities of fuels, the most direct way is to categorize different types of fuels into several model arrays with the differences selected on the basis of fire behavior and on comprehensive coverage of fuel arrays. Such categories have and are being developed as part of the National Dire Danger Rating System and presently include eleven fuel models. These models are described in Reference 1 and are distinguished from each other according to type, loading and sizes of fuels. Such models represent the most practical means for rapid description of fuel arrays and are particularly useful for assessing pollutant emissions produced by past wildland fires.

2.2 Prediction of Rates of Fire Spread

Rate of fire spread represent one of the most inadequately analyzed parameters required. For example, Rothermel (1), considers that the rate of fire spread equals the ratio of the "propagating heat flux" divided by the energy required to ignite a unit volume of the fuel. Similar approaches have also been used by Thomas (2) and by Woolliscroft (3). Perhaps the most disturbing feature of these analyses is the neglect of the fact that the flux various with distance beyond the fire front.

A more detailed spread criterion is afforded by the model of Albini (4) which assumes that the total outgassing (moisture and fuel vapor) is directly proportional to the incident flux. Unfortunately, this approach does not consider the sensible heat absorbed both prior and during pyrolysis. In addition, the analysis does not provide for the heat reradiated or convected away from heated fuels as the outer layer of wood heats. This heat loss could be quite large. Finally, none of the above analyses deals with the very difficult problem of predicting flame propagation through variable mixtures of fuel vapors and air.

These observations and the fact that the experimental and theoretical spread rates usually differ by a factor of 2 or more (5,6) emphasizes the need for more careful work. Unfortunately, as indicated by the paper of Hottel (7), the problem of predicting the rate of fire spread has not been resolved for the case of radiant/convective heating, let alone for the case of firebrands.

Until better predictive means are available for predicting rates of fire spread, it is recommended that one predicts the rate of fire spread by using estimates of the burn times and of the area burnt. If the estimates prove too uncertain, it is recommended that one use the above estimates or spread rates for similar fuels and conditions, to assess whether the spread rate will be typically low, average or high as defined below:

- Typical low speed (12) = 6.2 ft/min.
- Typical average speed (see below) = 21.0 ft/min.
- Typical high speed (12) = 71.0 ft/min.

The average speed here was calculated so that it was equidistant percentage wise between the extreme speeds. High-spread rates are associated with fine-grass and fine-grass mixtures and high winds, while low speeds are associated with slash-type fuels with low winds. To treat cases for which burn data are not available, it is recommended that one use the predictive scheme of Rothermel (1).

2.3 Factors Affecting Pyrolysis Ignition and Burning of Wildland Fuels

On the basis of the work of Kilzer and Broido (8), it has been found that cellulose (which constitutes the bulk of dry wood) breaks down upon heating in the following five steps:

1) Generation of noncombustible gases (H_2O, traces of CO_2, formic and acetic acids, and glyoxal) up to 200°C.

2) Dehydration of cellulose to "dehydrocellulose" between 200 and 280°C. Reactions are endothermic and products are almost entirely nonflammable.

3) Depolymerization of cellulose between 280 and 340°C, resulting in the formation of volatiles.

4) Decomposition of dehydrocellulose into gases and char residue via an exothermic reaction that becomes dominant at about 320°C.

5) Vigorous oxidation of charcoal above 500°C.

Most of the volatiles are produced between 300 and 400°C (9). The fact that the activation energies associated with the pyrolysis of cellulose are appreciably higher in air than in nitrogen (10) indicates that the rate of pyrolysis will differ somewhat depending on the amount of excess air. However, the effect is not large enough to receive further consideration.

Basically, there are three ranges of wood temperatures involved in spreading fire and in sustaining burning. These are (11):

1) Flame point: wherein the decomposition gases will burn if an external ignition source is present -- 225 to 260°C.

2) Burning point: wherein the decomposition gases will burn spontaneously without an external ignition source -- 260 to 290°C.

3) Flash point: wherein wood will ignite spontaneously -- 330 to 470°C.

To assess the conditions for sustained burning, items (1) and (2) are of critical importance -- item (2) because it indicates the temperatures that must be achieved by at least a portion of the fuel or other media if burning is to be sustained; and item (1) because it indicates the minimum temperatures that far out fuels must achieve to participate in the burning.

Involvement of fuels in fire occurs in two steps: the first being the initial heating of fuels forward of the flame front; and the second being the subsequent involvement of these fuels in flames. Most of the emissions produced by heated fuels forward of the flame front will eventually enter the convection column.

2.4 Estimation of Degree of Pyrolysis

Recognizing that fires can be treated in two stages, one of flaming and one of smodering, we will first discuss means for assessing the quantities of fuel vapor driven from wood during the passage of the flame front. In this regard one can approach the problem either from an experimental or analytical basis. Here, we shall discuss both approaches.

2.4.1 Approach Based on Experimental Results

One method for appraising the amounts of pyrolysis products is to first assess the heat release rates and then develop means for relating the two. In this regard Rothermel (1) summarizes data needed to predict the heat release rates per unit area of fuel bed. These results are presented in

Figure 13 of Reference 1 for various packing ratios of excelsior, and for 1/4" and for 1/2" wood cribs. Determinations of the heat release rates for intermediate size fuels requires interpolation. Extrapolation to larger size fuels may be had by using the analytical approach discussed in Section 2.4.2. Data needed to account for the presence of moisture and mineral content are documented in Figures 7 and 8 of Reference 1.

The only drawback with this method is that it does not provide any thermal description of the wood after flame passage. This, of course, makes application to mixed fuels difficult and is important to predict smoldering reactions after flame passage. Overall, this approach appears to be the most satisfactory of the approaches presently available even though it requires data or additional analysis relating the heat release rates and amounts of pyrolysis products. The primary advantage of this approach is that one can take advantage of existing heat release data and thereby circumvent the very complex problem involved with fuel arrays.

2.4.2 Preliminary Analysis of Degree of Pyrolysis

Another method for predicting pyrolysis is to analyze the effect of thermal fluxes on the fuels. Here we shall briefly suggest the kind of analysis we have in mind. Since the evaporation of water largely controls the temperature profile through wood, let us assume that a quasi-steady-state condition exists in which heat absorbed at the surface of the fuel is conducted in a steady-state fashion into the depth at which water is being evaporated. This assumption is considered reasonable in that only shallow depths are involved and is satisfactory for interim determinations of the surface temperatures. Also we shall neglect variations of the flux over the surface of the fuel. As a result:

$$q - \xi \cdot \sigma \cdot T^4 \cong K(T-T_b)/x \qquad \text{(C-1)}$$

where:

q = flux absorbed by fuel surface

ξ = emittance of surface of fuel

σ = Stefan-Boltzmann Constant

T = absolute temperature of surface of fuel

K = thermal conductivity of fuel

T_b = absolute temperature of fuel at depth of boiling given by x

x = depth beneath surface of fuel at which water is being evaporated

If ξ is taken as 1, and K is taken as 0.1 Btu/ft-hr-°F, then it is possible to evaluate the surface temperature T as a function of the depth x for various values of q. To determine the depth of pyrolysis for various fluxes, exposure times and moisture contents of wood, one additional equation is necessary describing the effect of the incoming flux $(q - \xi \cdot \sigma \cdot T^4)$ on the depth of dehydration. To assess the effect of the incoming fluxes, we shall neglect the relatively small quantities of heat absorbed beneath the depth at which water is being distilled as well as the heat expended in vaporizing fuel vapors. Subject to this simplifying condition, the heat ΔQ required to drive the water from the depth x to x + Δx is approximately:

$$\Delta Q = \rho \cdot \Delta x \left[\left[\frac{T+T_b}{2} - T_o \right] \cdot C_f + M_f \cdot \left[Q_v + (T_b - T_o) \cdot C_w + (T - T_b) \cdot C_s \right] \right] \qquad \text{(C-2)}$$

where:

ρ = density of dry wood, lb/ft^3

x = depth of dehydration, ft

T = surface temperature, °R

T_b = temperature of boiling water, °R

T_o = initial temperature of wood, °R

C_f = specific heat of dry wood, Btu/lb-°R

M_f = ratio of weight of water of hydration to weight of dry wood, dimensionless

Q_v = latent heat of vaporization of water, Btu/lb

C_w = specific heat of water, Btu/lb-°R

C_s = specific heat of steam (constant pressure), Btu/lb-°R

Substituting:

ρ = 30 lb/ft^3

C_f = 0.46 Btu/lb-°R

Q_v = 970 Btu/lb

T_b = 212 + 460 = 672°R

C_w = 1.0 Btu/lb-°R

C_s = 0.5 Btu/lb-°R

into Equation C-2 and letting $T_o = 70 + 460 = 530°R$ results in:

$$\Delta Q = 30\ \Delta x\ [(0.23 + 0.5\ M_f)\ T + 776\ M_f - 89.2] \quad \text{(C-3)}$$

Here ΔQ varies with time and can be found from Equation C-1 as follows:

$$\Delta Q = (q - \varepsilon \cdot \sigma \cdot T^4)\ \Delta t \quad \text{(C-4)}$$

By integrating Equations C-2 through C-4 over time, it is possible to estimate the depth of dehydration as a function of q, exposure time, and moisture content M_f. The results of this endeavor are displayed by Figures C-1 and C-2 for fluxes of 10,000 and 20,000 Btu/ft^2-hr, respectively.

In each of the two figures, estimates are given for the depths of char (defined as the depth within which temperatures

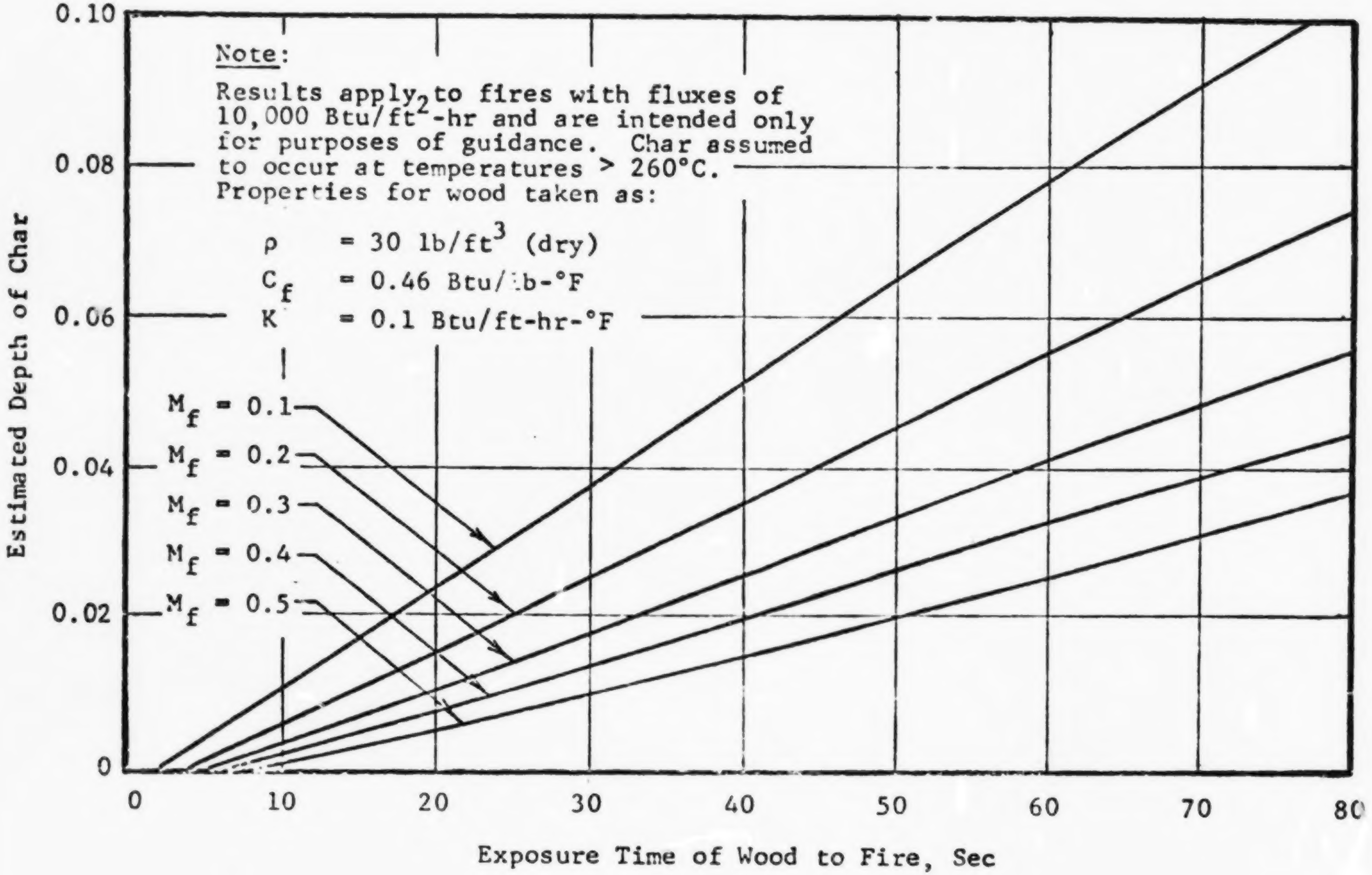

Figure C-1

ESTIMATED DEPTHS OF CHAR AS FUNCTION OF MOISTURE CONTENT AND EXPOSURE TIMES FOR FLUX OF 10,000 BTU/FT^2-HR

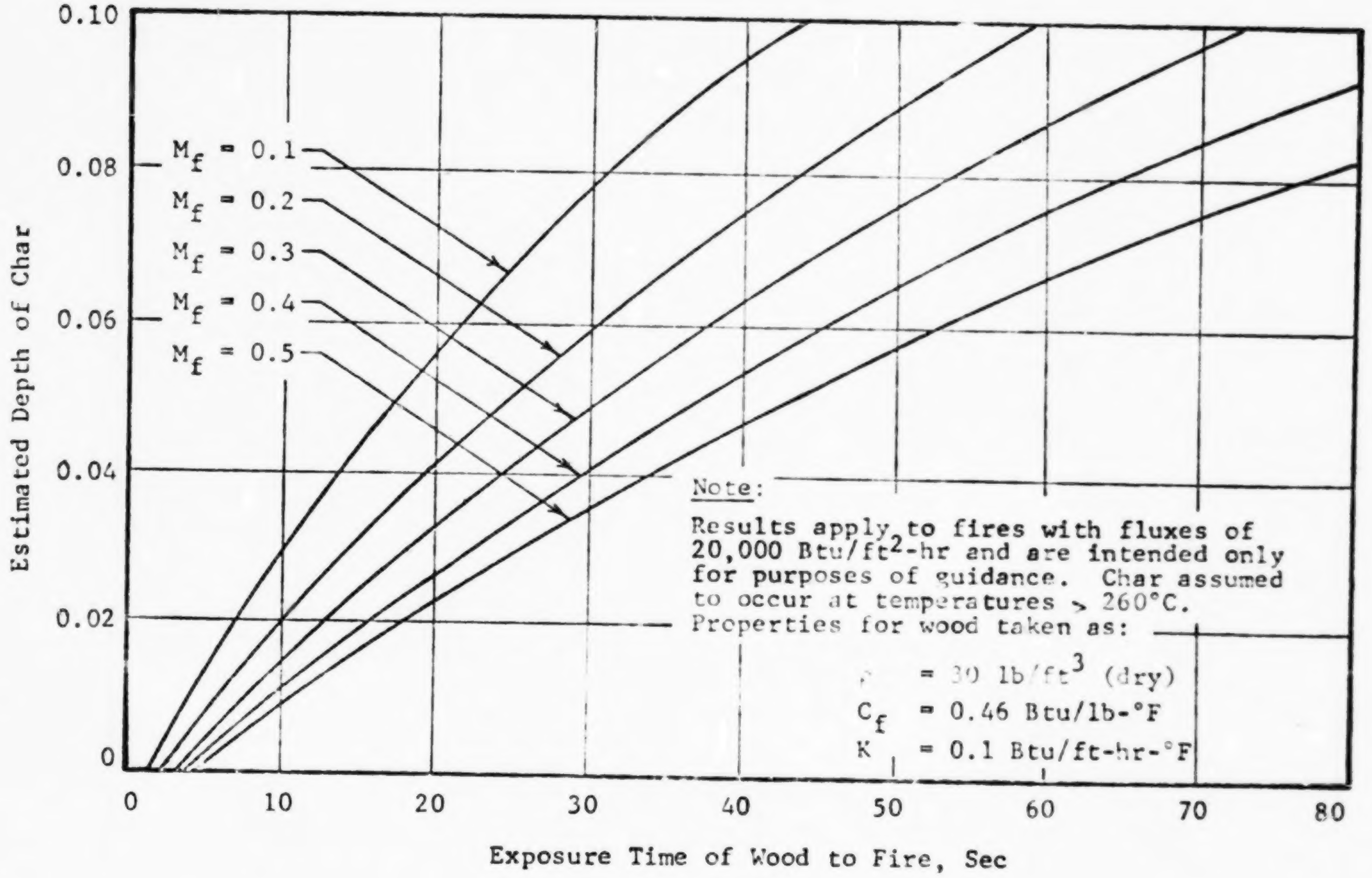

Figure C-2

ESTIMATED DEPTHS OF CHAR AS FUNCTION OF MOISTURE CONTENT AND EXPOSURE TIMES FOR FLUX OF 20,000 BTU/FT^2-HR exceed 260°C) as a function of exposure time to the stated fluxes for various moisture contents of the wood. Here M_f refers to the ratio of the weight of free water to the weight of dry wood. Exposure times (commonly termed reaction time) associated with rapidly spreading fires are of the order of several seconds (12) while exposure times associated with slowly spreading figures are of the order of several tens of seconds (12). Additional information pertaining to exposure times are available in Reference 1.

Fires with the flux of 10,000 Btu/ft^2-hr used in Figure C-1 are typical of most wildland fires while fluxes of 20,000 Btu/ft^2-hr are typical of large fires. Considering that the exposures times are usually less than 100 sec, it may be seen that volatile fuels will be evolved from layers of the order of 0.1 in. or less during flame exposure.

To appreciate the consequence of the above results, it is necessary to consider how much of the volatile fuel will be driven out of char. Such data are illustrated in Table C-1. Since we have used the arbitrary temperatures of 260°C in defining the lower boundary of the char, the data in Table C-1 indicate that 60 percent or more of the wood within the layers of char illustrated by Figures C-1 and C-2 would be pyrolyized. Activation energies and frequency constants for the first-order decomposition of wood indicate the above reactions are culminated in a matter of a few seconds (17) after the wood achieves the stated temperatures. The above analysis represents a preliminary examination of the problem of predicting the amount of pyrolysis produced during passage of the flame frant. Thin fuels such as grass would be totally consumed. In order to achieve accurate results, more detailed analysis along with experimental checks are requires.

Next, it is important to consider emissions produced after the passage of the flame front, namely emissions released by residual burning of incompletely pyrolyized fuels and by oxidation of char. While analysis can be used to predict such emissions, it is highly complex in that it requires prediction of the degree of oxidation or reaction of volatiles during passage through burning char. This problem can best be resolved by chemical analyzing the gases and particulates produced experimentally by a variety of glowing fuel arrays under various realistic combustion conditions. Such experiments would also be valuable in indicating the extent to which the pyrolysis and oxidation continues for each of the fuel situations.

Table C-1

DECREASE IN WEIGHT OF WOOD ON HEATING*

Heating Temperature, °C	Weight Loss (Volatile Products of Distillation),%	Heating Temperature, °C	Weight Loss (Volatile Products of Distillation),%
160	2.0	220	32.5
170	5.4	230	44.6
180	11.4	240	49.2
190	18.0	250	51.3
200	22.9	260	58.8
210	26.9	270	62.9

*Results presented in Chapter XXV in book by N. I. Nikitin.

3. DESCRIPTION OF CONVECTION COLUMNS

In order to predict the consequence of combustion on the products of pyrolysis, one must appreciate the types of environment through which the products will be exposed. Of concern here are the temperatures, residence times (or flame length and speed), mixing, and oxygen content associated with the convection column. To this end, we shall first discuss the applicability of fire modeling.

Modeling of fires involves the attempt to scale parameters such as gas density, heat input and distance so that one can use measurements from small well-defined fires to predict the characteristics of large-scale fires. Much work has been conducted in this regard (13,14,15). Most models assume a given rate of heat release over a given area of ground and use dimensional analysis to determine how the characteristics of the convection column vary with the variables. The result is scaling laws to translate data from one fire to another according to fire intensities and shape of burn area. Because of the complex phenomena involved in the formation of convection columns, care must be exercised in using scaling laws. Whenever possible, scaling laws should be checked against full-scale test data.

Lengths of flame L, of course, have a direct bearing on residence time and are frequently predicted using the following expression:

$$L = C \cdot Q^{2/3} \qquad \text{(C-5)}$$

where:

C = constant of proportionality

Q = rate of fuel or heat release per unit length of fire front

In order to better appreciate the accuracy of this relationship, field test data were taken from References 12 and 19 and plotted as shown in Figure C-3. Here we have fitted the data with curves assuming the flame length is proportional to $Q^{2/3}$ and to $Q^{1/3}$. Two points should be observed. The first is that the data are not consistent. This is not at all unusual based on IITRI's experiences with large liquid-fuel fires (400 to 2000 ft^2) which are much more reproducible than wildland fires. Secondly, it should be observed that somewhat better agreement is had by relating flame length to $Q^{1/3}$ than to $Q^{2/3}$. This result also agrees with the results of fires from circular pools of liquid fuels (18,19).

These liquid fuel baths ranged in size from tenths of centimeters to a few thousand centimeters and covered all flow regimes from laminar to turbulent. Over these regimes the ratio $L/Q^{1/3}$ fluctuated by ±50% without an abvious trend, while the ratio $L/Q^{2/3}$ constantly decreased with fire size by almost two orders of magnitude.

The effects of wind on flame length may be seen by the five data points of Figure C-3 for which wind data are available. For these data wind does not appear to have a pronounced effect on flame length. Therefore, at least for the present, it is recommended that the flame length be predicted without consideration of wind as follows:

$$L = 0.13 \cdot Q^{1/3} \qquad \text{(C-6)}$$

where:

L = flame length in meters

Q = rate of heat generation per unit length of fire front, cal/cm-sec

From IITRI's experiences with liquid-fuel fires, flame temperatures will peak within a few feet of the fuel and then gradually decrease with height. However, because such temperatures fluctuate widely with time, it is difficult to estimate the residence times associated with the flame temperatures. In view of this fact, it is recommended the flame

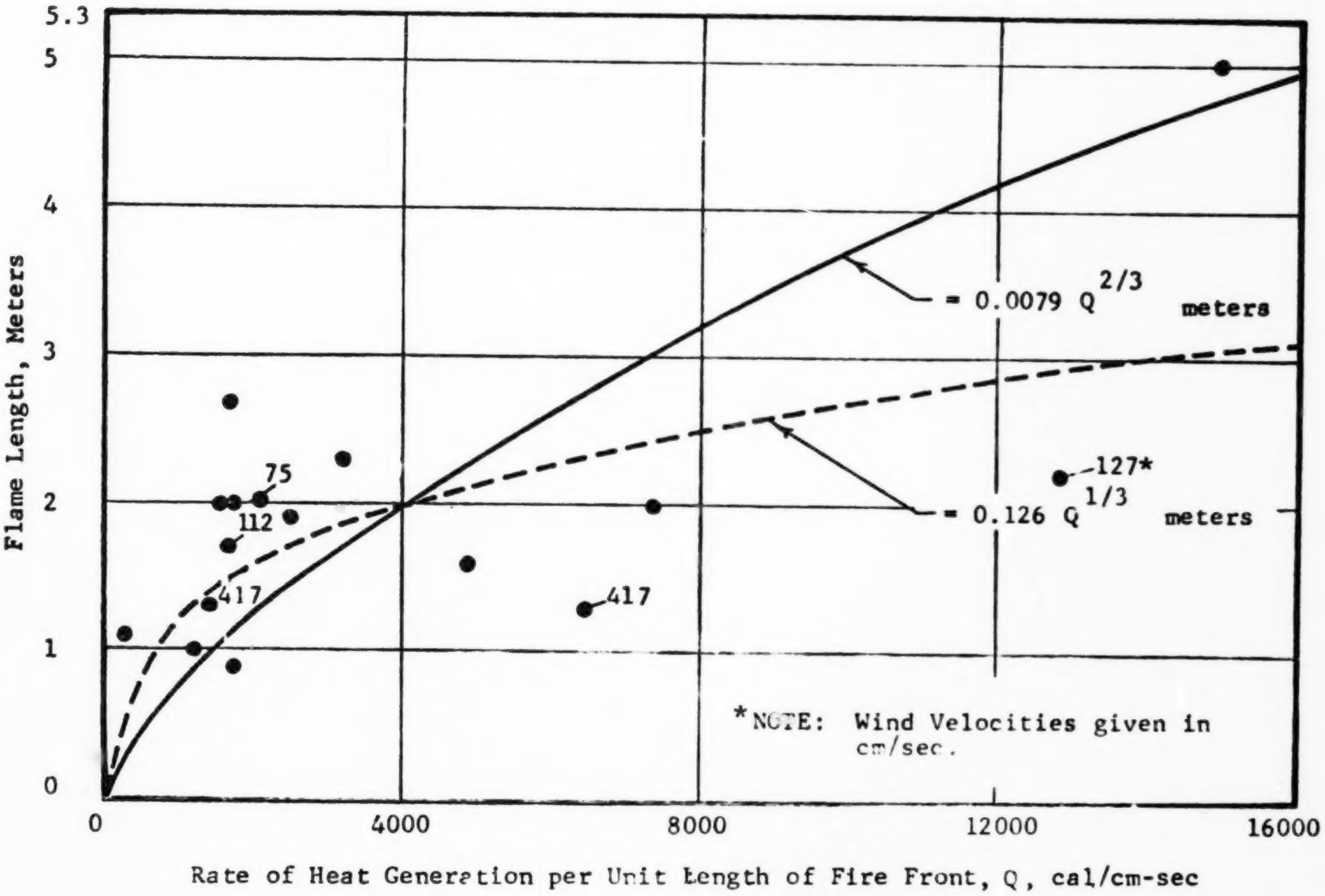

Figure C-3

FLAME LENGTH VERSUS RATE OF HEAT GENERATION temperature be considered constant at least until more detailed information becomes available. In this regard, References 12 and 19 present the mean temperatures for nine tests. These are 1055, 1050, 1080, 940, 1050, 1070, 1010, 1080, and 1070°C for an average of 1045°C (1913°F). While this mean temperature seems somewhat high, its use is recommended until more detailed data are available.

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